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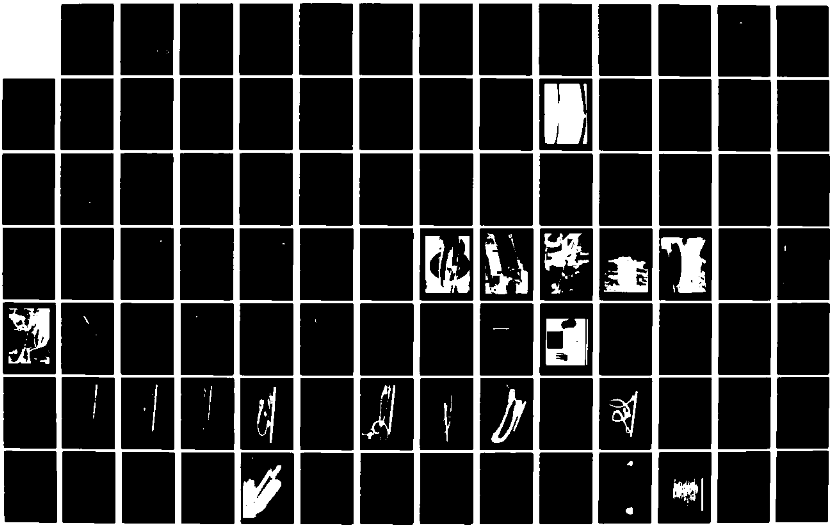

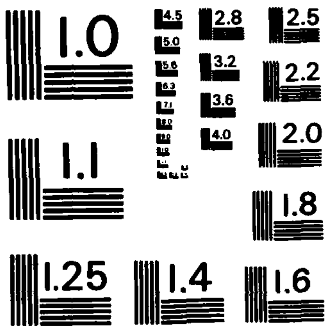
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KEVLAR CABLE DEVELOPMENT PROGRAM

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OCEAN TECHNOLOGY
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FOREWORD

In the past, cables and wire rope were made principally from steel, and high-strength lines from nylon and polyester. A new material, Kevlar*, which has unique properties in strength, stretch, weight, fatigue resistance and compliance, is now available. When this new material is included in the requirements of cables and lines, substantial savings and increased capability may be achieved.

Considerable progress was made in a NAVFAC-sponsored, five-year program completed in FY75 to develop cable technology for suspended sensor applications (Swenson, 1975). The principal focus of the program was to develop the analytical techniques to engineer cables, investigate various materials and cable design, and test these designs in cooperation with various sea experiments. This program clearly established that Kevlar made an excellent load-bearing material in certain types of cables for underwater suspended applications. The thrust of this follow-on, three-year program was to investigate Kevlar as a load-bearing member in general cable and rope applications.

Ralph R. Goodman

DR. RALPH GOODMAN
TECHNICAL DIRECTOR
NORDA

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EXECUTIVE SUMMARY

This report covers FY76 progress made in assessing and utilizing Kevlar fibers as tension members. Not all developments in this report were supported by the cable development program, but are included because they are directly related.

Included in this report are some basic assessments of the fiber and the rope construction, improvements in conductor design and bonding techniques, more reliable methods of cable termination, and, finally, the construction and use of these new ropes and cables.

This work has succeeded in developing both an increased industrial capability to provide components, and a greater awareness in the naval community of the advantages of Kevlar in suspended or tow cable applications.

PREFACE

This report describes the work sponsored by the Deep Ocean Technology (DOT) Program, cable development task, and was performed under NRL Project No. 81S01-86, Kevlar Cable Development Program. The principal investigator was R. C. Swenson (Code 8140), Navy Task No. 16279; the program manager was P. H. Cave, Naval Facilities Engineering Command (NAVFAC). Sea operations were conducted in conjunction with various Navy programs. The major sea operation carried out in FY76 was a cooperative effort of Naval Underwater Systems Center (NUSC); Naval Research Laboratory (NRL); and the Defense Scientific Establishment, New Zealand.

The author expresses his appreciation for the fine support and cooperation extended to this project by the participating personnel of the Defense Scientific Establishment, the crew of R/V TUI, and, particularly, to the New Zealand Chief Scientist, Dr. Richard Bannister.

TABLE OF CONTENTS

	PAGE
LIST OF ILLUSTRATIONS	iv
LIST OF TABLES	vi
I. INTRODUCTION	1
II. BRAID DEVELOPMENTS	1
A. Strength	2
B. Modulus of Elasticity	6
C. Cyclic Tension	6
D. Cyclic Bending	6
E. Conclusion	11
III. CONDUCTOR DEVELOPMENT	13
A. Materials	13
B. Construction	13
C. Testing	16
D. Conclusions	24
IV. CONDUCTOR INSULATION BONDING	25
A. Tie Material Development and Testing	25
B. Conductor Sample Description and Preparation	27
C. Pressure Testing	27
V. SEA EXPERIENCE SUMMARY	29
A. Woods Hole Oceanographic Institute	29
B. Mobile Acoustic Range Buoy	32
C. Project ANZUS Eddy	32
VI. SUSPENDED KEVLAR ARRAY TECHNOLOGY EVALUATION	36
A. Background	36
B. South Pacific Ambient Noise-3 (SPAN-3)	36
C. Hardware Description	39
D. Sea Operations	45
E. Conclusions	51
VII. PREPACK, FREEFALL BUOY SYSTEMS	54
VIII. LONG-TERM TENSION FATIGUE	57
A. Parallel Fiber Rope	57
B. Braided Rope	57
IX. HIGH STRENGTH ROPE	59
X. CABLE END FITTINGS AND ACCESSORIES	60
A. End Fittings	60
B. Splices	61
C. Stoppers	66
D. "V" Pullers	70
E. Conclusions	70
XI. OTHER DEVELOPMENTS	72
A. Naval Underwater Systems Center Uniline Bending Test	72
B. Coaxial Electromechanical Kevlar 29 Cable-Braid vs. Serves	72
C. Fairings	77
D. Wet Tension Fatigue	82
E. Kevlar Rope Design Guide	87
F. NAVSEA Kevlar Coaxial Cable Development Program	87
XII. SUMMARY	95
REFERENCES	97
DISTRIBUTION LIST	99

ILLUSTRATIONS

		Page
Figure 1.	Various Parameters to Consider When Constructing a Braided Rope	3
Figure 2.	Effect of Braid Angle (α) and Crimp Angle (θ) on a Rope's Strength Conversion Efficiency	5
Figure 3.	Effect of Braid Angle (α) and Crimp Angle (θ) on a Rope's Modulus Conversion Efficiency	7
Figure 4.	Effect of Braid Angle on Cable Bending Fatigue Life	10
Figure 5.	Combined Elastic and Plastic Elongation Effects on Standard Coaxial Core	14
Figure 6.	Construction of Conductors Used in Tension Cycling Elongation Tests	15
Figure 7.	Load-elongation Curves for Various Test Materials (Single Conductors)	17
Figure 8.	Load-elongation Curves for Various Test Materials (Twisted Quad Conductors)	18
Figure 9.	Composite Conductor Test Cable	20
Figure 10.	Load-elongation Curves for Composite Conductor Test Cable	21
Figure 11.	Elastic Deformation vs. Lay Length for Conductors with Two Different Insulations	23
Figure 12.	Schematic Diagram of Various Combinations of Insulating Materials, Primers and Substrates in Pressure Test Tank	28
Figure 13.	Configuration of Shallow Water Test Buoys	30
Figure 14.	Mobile Acoustic Tracking Range Buoy	33
Figure 15.	ANZUS Eddy Acoustic Array	35
Figure 16.	Various Kevlar Array Configurations	37
Figure 17.	Chart of Array Positioning	38
Figure 18.	Cable, Hydrophone, Spreader Cage and Canvas Boot	40
Figure 19.	Array Cable Coiled in Crib	41
Figure 20.	Application of Flat Kevlar Strands to Form End Fitting	42
Figure 21.	Cast Steel Anchors with Cross Rails Used in the Horizontal Mode	43
Figure 22.	Neoprene "V" Groove Segments Fastened Between Plates and Fixed to a Capstan	44
Figure 23.	MABS Vertical Deployment	46
Figure 24.	Stopper Being Applied to an Electromechanical Cable During Operations at Sea	47
Figure 25.	MABS Horizontal Deployment Illustrating a Coaxially Inserted Hydrophone	48
Figure 26.	Acoustic Positioning of Array	49
Figure 27.	Visual Representation of Array Position	50
Figure 28.	MABS Installation Parameters	52
Figure 29.	MABS Depth Record	53
Figure 30.	Free-Fall, Self-Locking Cable Dispenser for Ocean Buoy Systems	55
Figure 31.	Canister, Weight, Cable Hook, Shear Pin and Cable Bale of the Prepack Buoy System	56
Figure 32.	Lifetime and Creep vs. Deadweight Load	58
Figure 33.	Phillystran Braided Cable with a Micropress End Fitting Pulled to Destruction	62
Figure 34.	Phillystran Braided Rope with an Eye Splice Which Survived the Epoxy Potted Termination	63
Figure 35.	Phillystran Braided Rope and Preformed Dyna-Grips Pulled to Destruction	64
Figure 36.	Phillystran Braided Rope in Which the Braid over Rod Survived the Braid Through and Over a Cone End Fitting	65
Figure 37.	Phillystran Braided Rope with Eye Splices, Each Made with Four Lengths of Parallel Aramid Fiber	67

ILLUSTRATIONS (Cont'd)

Page

Figure 38. Nolaro 1/4 Inch Polyester with Eye Splice Termination. Rope Failed in Center of Test Section 68
Figure 39. Parallel Fiber 3/4 Inch Aramid Cable with Eye Splices. Cable Failed in Center of Test Section 69
Figure 40. Two End of a Braided Rope, Each with an Eye Splice, Braided Together to Represent a Mid-Line Splice 71
Figure 41. Bending Cycles to Failure for 3.8 cm Ropes Over 3.96 m Sheave 73
Figure 42. Load-Elongation Curves for Braided Kevlar Cable 74
Figure 43. Load-Elongation Curves for Served Kevlar Cable 75
Figure 44. Coaxial Cable Failure Mode 76
Figure 45. Double Armored Steel Cable Overbraided with Nylon Jacket and Fairing to Reduce Strumming 79
Figure 46. Results of Creep Measurements for Kevlar Fiber (1500 Denier Yarn) 83
Figure 47. Strand Test Frame 85
Figure 48. Strand Termination 86
Figure 49. Kevlar Braided Coaxial Pilot Cable 89
Figure 50. Five Candidate Coaxial Cables 91
Figure 51. Final Design of Coaxial Cable 94

TABLES

		Page
Table 1	Test Cable Characteristics	4
Table 2	Reverse Bend Cycling Test Results for Impregnated Braids	9
Table 3	Cyclic Bend Over Sheave Cable Tests	12
Table 4	Cyclic Bend Over Sheave Braid Tests	12
Table 5	Cable Cyclic Axial Tension Test Results	22
Table 6	Cable Flex Over Sheave Test Results	22
Table 7	Formulated Compound Properties	26
Table 8	Loss of Strength at Various Loading Conditions and Exposure Times	31
Table 9	Kevlar Cable Tensile Tests	34
Table 10	Time to Failure vs. Dead Weight Load	57
Table 11	Results of Multicore Uniline Tests	59
Table 12	Summary of Cable Strumming Data	81
Table 13	Strength Loss Under Load in Sea Water or Air	88
Table 14	Cyclic Bend Over Sheave Cable Tests	93

I. INTRODUCTION

An assessment of Kevlar cable and rope performance was conducted during a Kevlar workshop held in conjunction with the 1975 Offshore Technology Conference. The consensus was that Kevlar performed well and merited serious consideration for a wide variety of applications.

During the past three years considerable exploratory laboratory testing on Kevlar ropes and cables in various forms and construction was reported, but little sea usage experience existed. The constructions, which allowed for Kevlar's properties of no-yield, low-transverse modulus and self abrasion, were reported to produce good cables which reduced overall system cost with higher performance. Polyurethane impregnated braids and parallel-strand constructions appeared to be the most favorable.

The Naval Facilities Engineering Command (NAVFAC) Kevlar Cable Development Program was initiated as a result of promising developments which showed the feasibility of using Kevlar tension members in various explicit applications. The objective of this program was to develop Kevlar mechanical and electromechanical cables for general naval applications. It capitalizes on Kevlar's unique properties of high strength-to-weight ratio, high fatigue life, compliance, non-corrosion, and low elongation, while appeasing weaknesses in low transverse modulus, no-yield, and self-abrasion. The principal focus was on flat braids and parallel constructions. The approach was to design and test various constructions in the laboratory and to integrate components in various sea operations to gain much needed sea usage experience.

The FY76 effort was divided into four areas. The first area reported the results of various tasks now completed from the past Cable Development Program for Suspended Sensor Applications. The second area monitored and summarized ongoing developments in related programs. The third area described a major sea experiment which completely utilized Kevlar cables and ropes, and the fourth area initiated new starts in various components and testing. This report summarizes the results of the first year's effort of this three-year program.

II. BRAID DEVELOPMENT

It was not intuitively clear that the construction of braided ropes would be a good application for Kevlar aramid fiber tension members. The anticipated problems of self-abrasion, low transverse modulus and constructional elongation would appear to limit the use of this fiber. Early trial samples, however, which accommodated those weaknesses by means of an impregnated, non-twisted strand, produced surprisingly good results in strength conversion efficiency, elastic elongation, and cyclic tension fatigue. The key element in the design was to allow the strand to flatten at the braid crossover points to reduce the compressive load. Any transverse loading accentuates the low transverse modulus and abrasion weakness of Kevlar. Trial braid samples, constructed of highly twisted strands which tried to maintain a cylindrical cross section as tension was applied, produced poor results. The increased bearing area markedly increased braid performance at the crossover points of a flat braid design which reduces the crimp angle (Swenson, 1975).

The principal merits of braided Kevlar are:

- Ease of fabrication, which requires considerably less precision and risk than alternative construction, i.e., accommodates the no-yield and high modulus problems requiring precise tension control as in serves and parallel construction.
- Self-limitation of the effects of strand damage and elimination of the requirement of continuous strand length. Local imperfections and individual strand damage are averaged over a short length of the cable. Even if each strand is cut many times along the length of the cable, only a slight decrease in cable strength will result as long as the cuts are separated by several feet.
- Easy end fittings with epoxy-potted conical sockets or with braid grips.
- Accommodation of a wide variety of core sizes.
- A wide range of strength through choice of strand sizing, braid design, and number of layers.
- Excellent cyclic-tension fatigue life at high stress levels.
- Low elastic stretch that can be accommodated by properly designed conductors.
- Flexibility and small bending radii.
- Excellent cost effectiveness, within certain ranges, in relation to alternative material and strength requirements.
- Non-torque cables.
- A large industrial capability to produce braids in existing equipment.

The early test results, along with the many desirable features of braids, lead to a more concentrated effort in analytical modeling (Phoenix, 1974a, and Phoenix, 1974b) and experimental validation in which the

principal braid parameters were studied. There are many braid parameters to consider, as can be seen in Figure 1. Among these are type of braid, type and size of strand and whether it is impregnated and/or lubricated, number of carriers and ends per carrier, picks per 2.54 cm, crimp angle, braid angle, number of passes, etc. Obviously, all of these cannot be evaluated in a modest effort. The effects of braid and crimp angle on elongation, strength, cyclic tension fatigue, and bending fatigue were thus the principal parameters considered in a test series utilizing polyurethane impregnated non-twisted strand.

The mathematical analysis of Kevlar braid made certain pertinent assumptions necessary for review before describing the verification experiments.

- Each one of N braid ends travels in a helical path with helix radius R and helix angle α. N/2 ends form left-traveling helices and N/2 ends form right-traveling helices.
- The braid core elastically resists radial contraction. The core does not carry any axial load.
- The untwisted strands compress transversely at crossover points. The strands weave over and under at some angle θ called the crimp angle.
- Strand modulus E_o is related to fiber modulus E_f by $E_o = E_f P$, where p is the packing factor usually assumed to be approximately 0.81.
- The tensile strength of any braided rope σ_γ is easily correlated to any other braided rope by the nondimensional ratio σ_γ/σ_s where σ_s is the strand tensile strength.
- In a similar fashion the modulus of a braided rope/E_r is best represented by the ratio E_r/E_s, where E_s is the strand modulus.
- The report is equally adaptable from $\frac{1}{1}$ diamond braid to both $\frac{2}{2}$ regular and $\frac{3}{3}$ Hercules braids.

Sixteen different models of braided electromechanical cable were manufactured for this series of tests by Philadelphia Resins Corporation (Uhrick, 1975). The basic strength member of all the cables was Phillystran PS-29-B75, a urethane impregnated, Kevlar 29, aramid fiber end having an equivalent diameter of 0.097 cm and a break strength of 1.334 kn. Thirty-two of these ends were braided over lengths of each of four cores into a 2/2 regular braid. The only variations in the braiding process were the braid angles. The cores consisted of four different grades with different hardnesses of thermoplastic rubber (TPR)*: TPR 1600; TPR 1900; TPR 2800; and a blend of TPR 2800 and TPR 1600. All the cores were extruded to a diameter of 0.89 cm. Table 1 lists the sixteen tested samples.

A. Strength

As previously mentioned, each of the thirty-two cable ends had a break strength of 1.334 kn. This means that the ideal ultimate strength of a parallel fiber rope, so constructed, would be 42.7 kn. The magnitude of the braid construction angles, however, determines the relative cable break strength.

Thirty-two specimens, each 1.52 m long, were terminated by epoxy potting heads. Care was taken to ensure that the braid and core were both under equal tension during the potting process. It was assumed that this 1.52 m length would be sufficient to equalize the individual strand tensions should a catenary exist within the braid structure. They were then tensioned and tested.

The resultant test data points were plotted on the theoretical curves (solid lines) taken from the study on mathematical modeling, and were in good agreement (Figure 2). As the mathematical modeling predicted, the cable strengths decreased as the braid and crimp angles increased. Comparison of the experimental data and the curves indicates a slightly lower actual tensile strength. The difference, however, in the two values is consistent throughout (14 percent), proving it to be an accurate method of prediction.

The difference in core hardnesses over the range selected had no effect on the test data. It appears that the core elongated proportionally to the braid due to its high elasticity. There were no ridges pressed into the core by the braid; therefore, the core must have been experiencing a reduction in cross sectional area along with the braid.

It is clear that the key parameters affecting a rope's strength translation efficiency are the crimp angle θ and braid angle α; an increase in either results in a reduction in strength.

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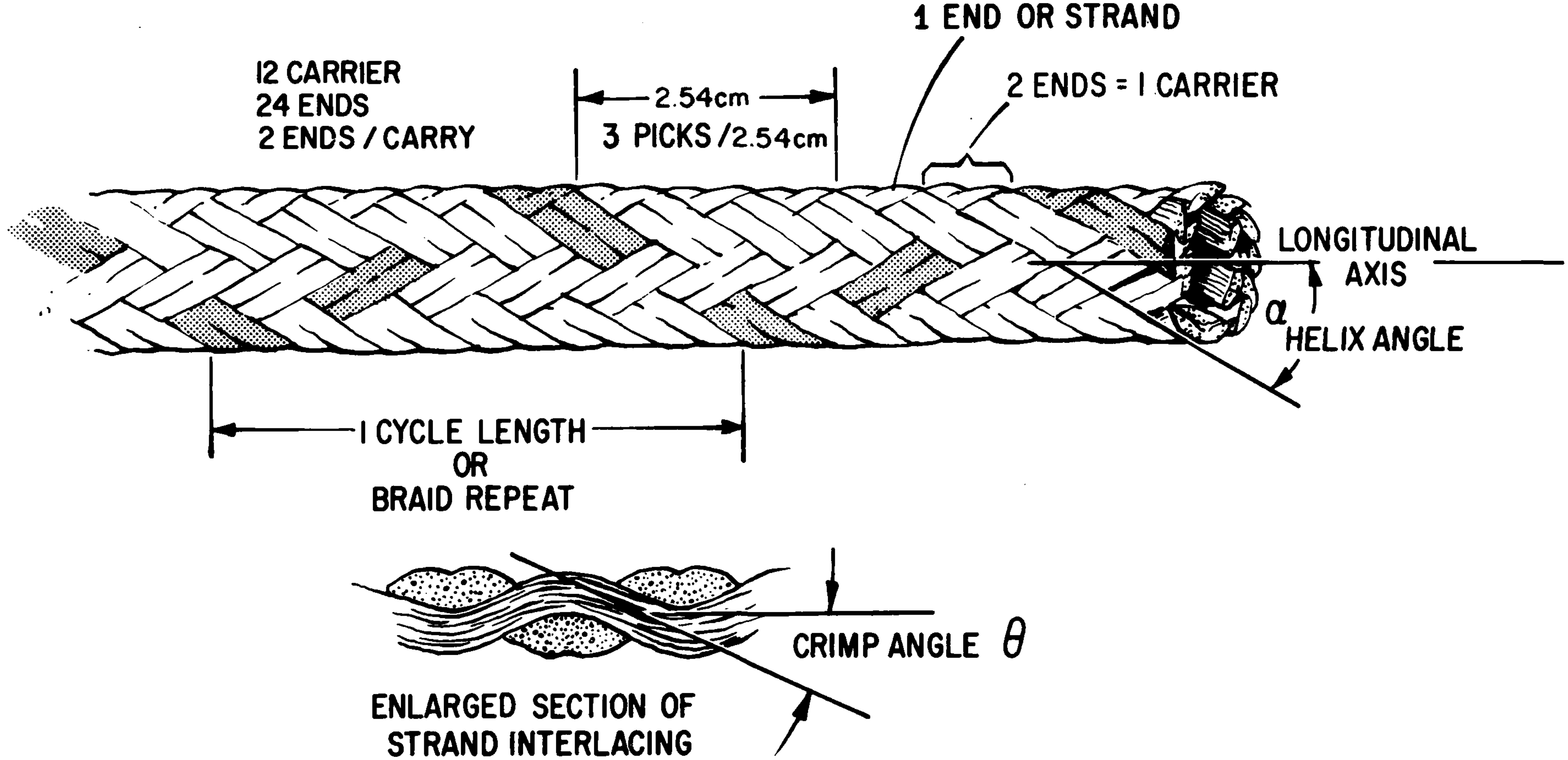

Figure 1. Various Parameters to Consider When Constructing a Braided Rope

Table 1. Test Cable Characteristics

Cable Number	Core Hardness (Shore A)	Helix Angle	Crimp Angle
1	65	14.62°	4.32°
2	65	21.82°	6.6°
3	65	28.88°	9.03°
4	65	36.63°	10.93°
5*	77	14.62°	4.32°
6*	77	21.82°	6.6°
7*	77	28.88°	9.03°
8	77	36.63°	10.93°
9	87	14.62°	4.32°
10	87	21.82°	6.6°
11	87	28.88°	9.03°
12	87	36.63°	10.93°
13*	95	14.62°	4.32°
14*	95	21.82°	6.6°
15*	95	28.88°	9.03°
16*	95	36.63°	10.93°

* Samples of these cables were also tested in the bend-over-sheave experiments.

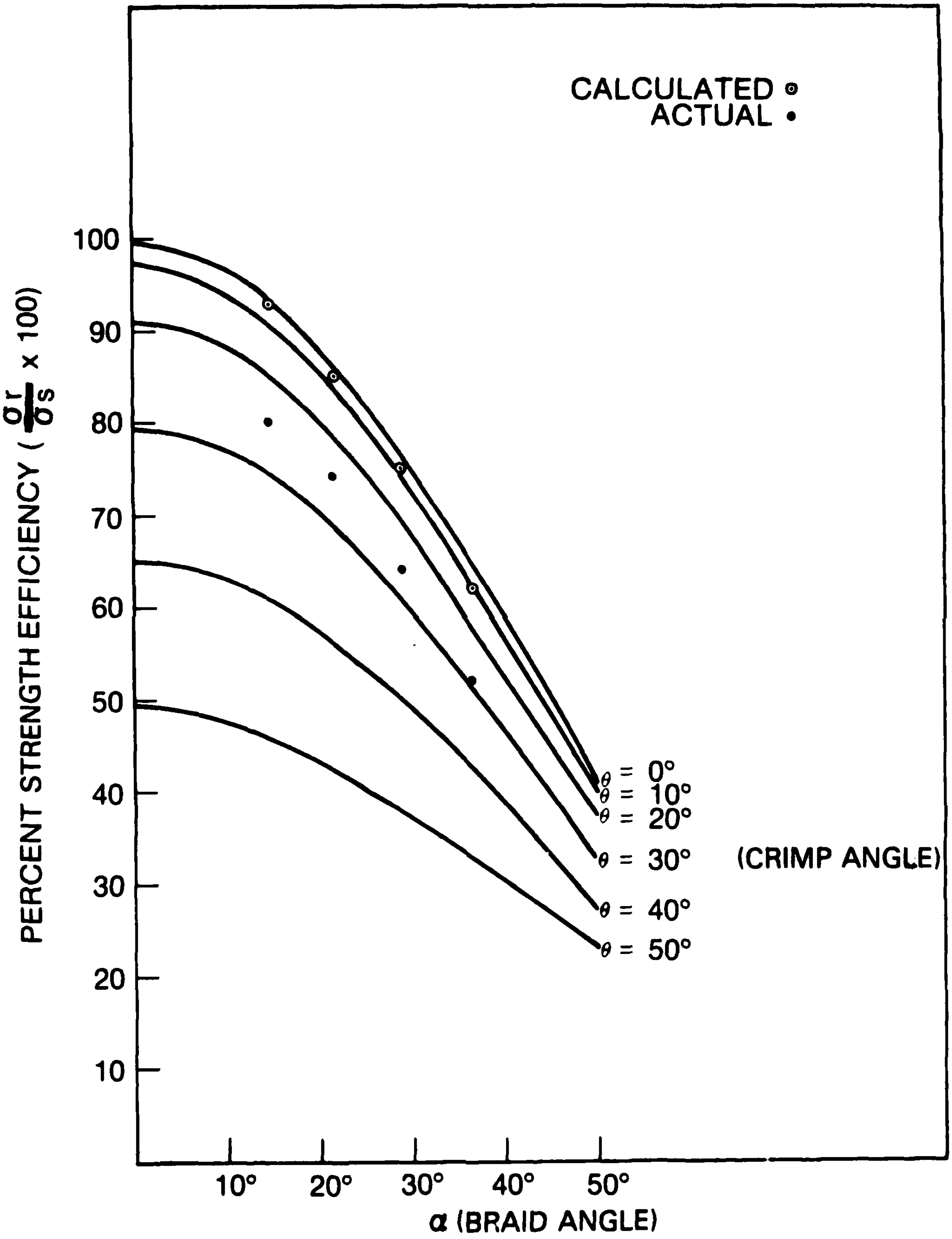

Figure 2. Effect of Braid Angle α and Crimp Angle θ on a Rope's Strength Conversion Efficiency

B. Modulus of Elasticity

One 3.05 m sample was selected from each of the sixteen cab'e constructions (Table 1) to obtain load-elongation characteristics. The test procedure for establishing a stress-strain relationship entailed cycling each cable ten times from 0-50 percent of break strength. On the first and the tenth loading cycle, several measurements were obtained and recorded. Again, as in the tensile tests, the core hardness made no observable difference in the results.

Stress-strain information provided the ropes' modulus of elasticity (E_r) which, when divided by the modulus of the ends (E_S), produced a figure of comparison. These empirical outputs were grouped by braid and crimp angle, then averaged and plotted (Figure 3). The solid curves in the figure are taken from the math model report. The actual and calculated data obtained from these tests are plotted on the curves, and, as can be seen on the graph, the tests do an excellent job of confirming the predictions.

Again, as in the strength translation efficiency loss, a rope's modulus is reduced with any increase in crimp angle θ and/or braid angle α. In addition, because the construction angles are determined in part by the cross sectional area A and the number of strands N, any attempt to increase the strength by increasing these factors will cause a marked decrease in modulus.

C. Cyclic Tension

Tension-tension cycling induces fatigue in a rope by continual tensile loading and unloading in a uniaxial direction. This is a common mode of failure for tension member materials subjected to oceanic wave action. However, the Kevlar fiber itself has inherently good fatigue properties. Problems with braids arose initially because of the previously discussed self-abrasion tendencies of the material. A large part of the answer was in strand impregnation and strand flattening; more is being done with construction angles, and even more remains to be done with lubrication. At this point, however, it can be said that cyclic tension has little or no effect on properly designed Kevlar ropes.

An early series of tests was performed on aramid fiber braided ropes of 9.34 kn break strength (Rice, 1974). One set of specimens was constructed of polyurethane-impregnated fiber, the other set of factory-coated, cordage-finished yarn. The conclusion was that after 15,000 cycles from 0-38 percent of the rope's ultimate load, the impregnated braid lost no strength.

Braided electromechanical cables with specially designed cores have also done considerably well. For example, a quad cable with three layers of braid was tested at a break strength of 70.281 kn. A sample of this cable was then subjected to more than a million cycles between ± 10 percent of a mean load of 5.916 kn. These tests are sufficient evidence of the amazingly high fatigue life of polyurethane-impregnated Kevlar at high stress levels.

D. Cyclic Bending

Cyclic bending of Kevlar braided ropes has been the weak point of an otherwise excellent rope construction. Studies show that it is not cyclic fatigue of the fiber that has caused the problems; rather, it is internal and external abrasion of the strands. Initial tests in which various constructions of Kevlar fiber ropes were cycled over a sheave (D/d=24) show that of the specimens selected, a long pick braid survived only one-half the number of cycles of a jacketed parallel construction rope and only one-one hundredth the cycles of a 19 x 7 wire rope construction.

The solution is being approached by several different methods. DuPont has performed a series of experiments intended to reduce or eliminate the abrasion problems of Kevlar mechanical ropes by varying the braid helix angle and by adding lubricants and/or jackets. In addition, a study was initiated by the Naval Research Laboratory (NRL), partially at its own facilities and partially under contract, to study the effects of sheave cycling of electromechanical cable on braids of various construction angles.

DuPont began their tests by observing the abrasion resistance of resin-impregnated Kevlar yarns with and without wax overlays (Riewald, 1977). Several types of urethane resins gave the strands much better dry abrasion resistance. The number of cycles to failure of the impregnated strands was an order of magnitude greater. The addition of wax overlays on the impregnated resins gave excellent improvement. The conclusions of the study were:

- Rope finish had shown the best dry/wet abrasion resistance of all the finishes tested.
- Nylon and Dacron were superior to Kevlar in bare fiber abrasion resistance (dry or wet) in yarn on yarn test.

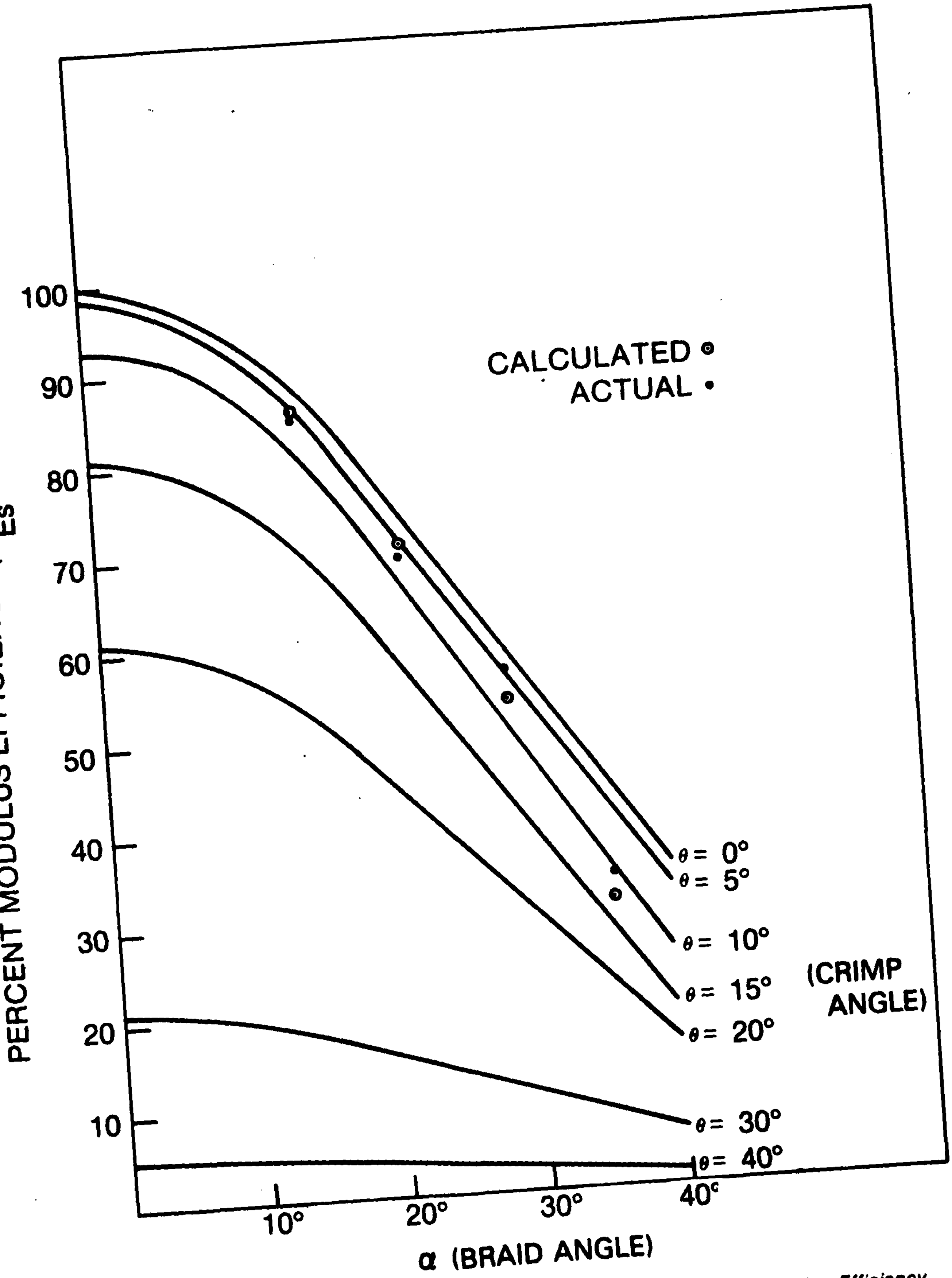

Figure 3. Effect of Braid Angle α and Crimp Angle θ on a Rope's Modulus Conversion Efficiency.

- Wet abrasion was less effective than dry for Kevlar, Nylon, and Dacron.
- Slight twisting of Kevlar (~ 3 turns per 2.54 cm) significantly improved abrasion resistance
- Several resins used for impregnation of the strands improved abrasion resistance.
- Wax overlays allowed a substantial increase in cycles to failure in impregnated strands.

Using the information obtained in the strand abrasion study, the next series of experiments were conducted on Kevlar ropes (Venkatachalam, 1976). This approach studied the benefits of solid lubricants having low friction coefficients as compared to wax overlays, and examined the advantages of jackets.

The solid lubricants included waxes, Molykote* spray, Dag 35**, and thick coatings of DuPont's rope finish. Applying large amounts of the rope finish caused problems due to occasional buildup during deposit formation and a tendency to fume during application. This was also because this type of coating lacked the durability of the lubricants.

Solid lubricants proved to be fairly durable, and also increased the fiber's resistance to failure by a large percentage. Dry abrasion resistance of the slightly twisted Kevlar yarns was then equal to both Nylon and Dacron, although the wet resistance of Dacron was still slightly better. Research for a more durable lubricant which can be applied prior to weaving the braid is continuing at DuPont. Until this research is concluded, the only short-term recommendation that can be made for improved abrasion resistance is to post-lubricate Kevlar ropes with any one of a number of commercially available resin bonded lubricants or waxes.

The second part of the study concerned jackets and jacketing materials. Because Dacron and Nylon have better bare-fiber abrasion resistance and can be easily applied during the rope braiding process, both were used to overbraid several aramid fiber ropes. The chafing tests revealed a very large increase (20X) in the number of cycles to failure with a 0.16 cm thick nylon jacket. The nylon covering, however, does nothing to improve the wet abrasion resistance. On the other hand, a 0.08 cm Dacron jacket not only made an equal improvement in dry resistance, but also bettered the wet-wearing qualities slightly over three times.

The third and last part of the braid study conducted at DuPont involved the reverse bend cycling of braided Kevlar ropes. At this point there were several variables to consider; two were held constant — the D/d ratio and all the tests were conducted dry. Table 2 lists the cycles to failure for the impregnated braids versus the unimpregnated braids; the jacketed ropes versus the unjacketed; the waxed versus the unwaxed; and, in addition, introduces the variable of helix angle. The general trend shows the larger helix angle, waxed ropes can survive the greatest number of cycles before failure.

The bend-over-sheave tests initiated by NRL were conducted on several of the cables discussed in Table 1. Seven of the 16 different types of cables were selected, since it had been determined that the range of core hardnesses used made little difference in the tension-tension data. Two specimens of each cable were wrapped 180° around a pair of test sheaves and attached end-to-end to form a continuous loop. The sheaves were 25.4 cm in diameter, which allowed a D/d ratio of 20/1. Each pair of specimens was loaded to approximately 20 percent of ultimate strength, and cycled back and forth with a 66 cm stroke until one sample failed. A dummy cable was then inserted in place of the broken cable, and the test continued until the second specimen failed.

Figure 4 shows the braid angle has a definite effect on the bending fatigue life. The points plotted on semi-log graph paper show the exponential rise in number of cycles to failure with linear increases in braid angle. For these braided cable tests, if x equals the magnitude of the braid angle and y equals the number of bending cycles to failure, then:

$$y = y_o e^{mx}$$

*Molybdenum Desulfide-Resin Bonded Lubricant, Dow Corning

**Graphite Resin Bonded Lubricant, Acheson Colloids Company

Table 2. Reverse Bend Cycling Test Results for Impregnated Braids

Load = 20% Ultimate						
Cable	Helix Angle	Load kn	D/d	Jacket Yes or No	Other Condition	Cycles to Failure
Impregnated Braids	14.6°	6.894	24	Yes		870
	14.6°	5.004	24	Yes		1284
	21.8°	6.500	24	Yes		1461
	21.8°	6.500	24	No		1686
	21.8°	6.500	24	No	11.4% Wax Overlay	66,375
	28.9°	5.783	24	Yes		5442
	28.9°	5.783	24	No	10.9% Wax Overlay	117,750
	36.6°	5.004	24	Yes		33,560
Unimpregnated Braids	12°	20% UTS	24	No		396
	12°	20% UTS	24	Yes		1320
	34°	20% UTS	24	No		1296
	12°	20% UTS	24	No	10-12° Wax Impreg.	13,000

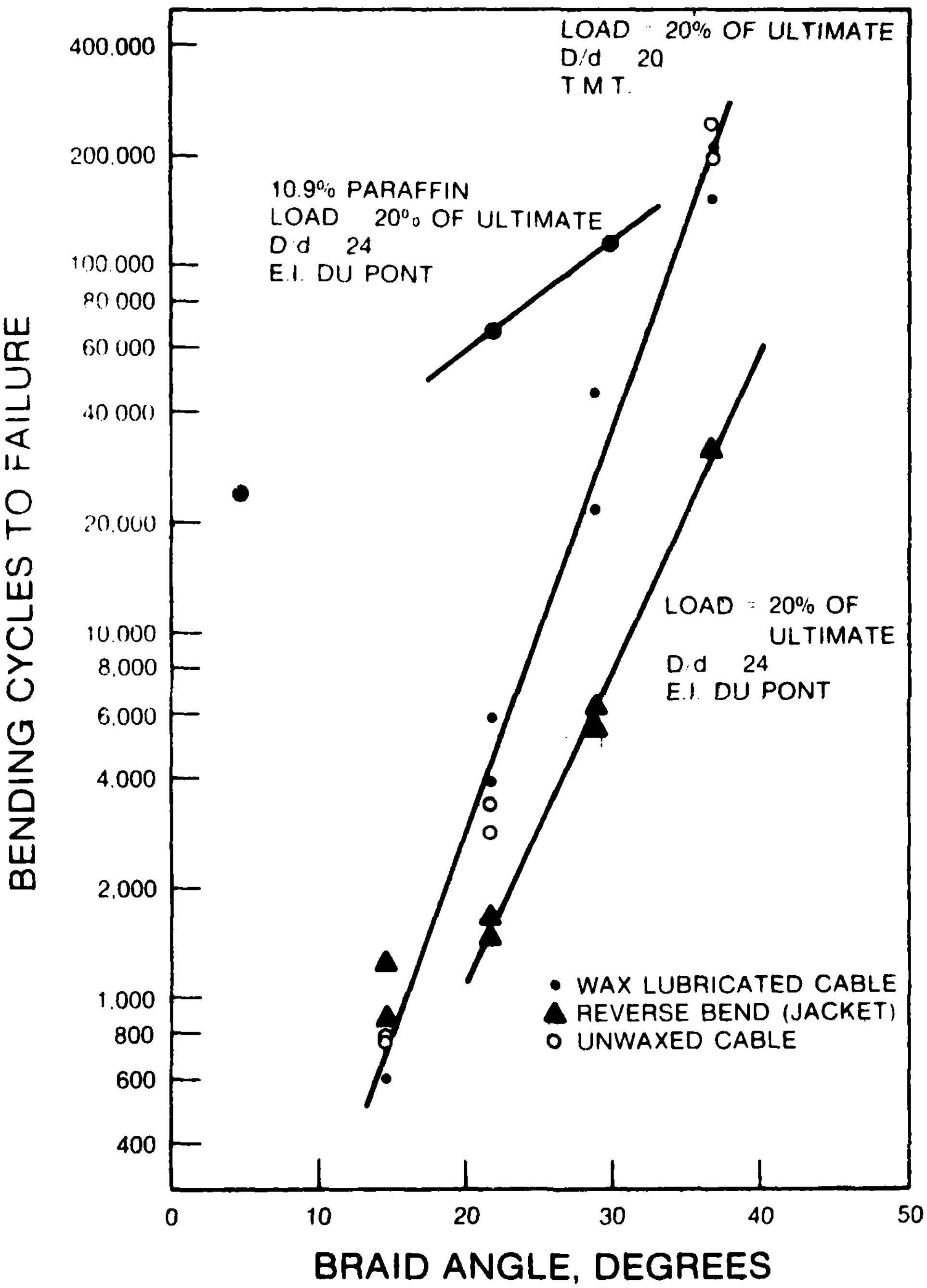

Figure 4. Effect of Braid Angle on Cable Bending Fatigue Life

In the case of the series of bend tests performed at Tension Member Technology* (TMT), y_0 = 16.7 and m = .25, and for the DuPont reverse bend tests, y_0 = 20.5 and m = .20. It must be pointed out, however, that these two sets of experiments are not directly comparable for several reasons. The TMT data points were obtained from single sheave bend test, DuPont's from double-sheave reverse bend tests which are more severe. The wax applied by DuPont was in solution, and thoroughly permeated the cable. The wax applied by TMT was the same general type recommended by DuPont, but the application technique apparently failed to provide the needed coverage. The series at TMT had only two variations, braid angle and wax; DuPont's suffered four different variations, wet/dry, wax/no wax, jacket/no jacket, and changes in braid angle.

Finally, several electromechanical cables were cycled over sheaves at NRL. These were not undertaken to test the braid, but rather the endurance of various type conductors within. However, more can be added to the data on braid lubrication and on the number of cycles versus tension.

Two layers of 15,000 denier impregnated Kevlar strand were braided over the various cores, and samples were then cycled over a sheave while under a tensile load until parting (D/d = 20). The two layers of aramid were in direct contact with each other, thereby causing a drastic decrease in the number of cycles to failure. Near twenty percent of its ultimate strength, the typical cable sample failed at about 2000 cycles. When the tension was raised to thirty percent of load, the number of cycles fell to about 150. At this point, Molykote was applied to the cable specimens to increase the time before rupture, which was almost five fold.

DuPont then took two samples of this same cable, applied waxes using an immersion technique, and returned them to NRL, where they were tested under the same conditions as the previous cables. They survived 3076 cycles and 2048 cycles, respectively, at thirty percent break strength. Compared to the previous tests, the waxing process improved the ability to undergo bending over a sheave by an average value of 5/1. (Table 3 lists the results.)

Finally, using all the information obtained from these studies, two test cables were developed for NAVSEA. One had a 25° braid, and the second a 30° braid. In both cases the strands were produced with a more elliptical cross section to reduce crimp angle, and had a silicone lubricant applied prior to the braiding process. The braid weave was tightened considerably and a nylon jacket was woven over the Kevlar strength members. The results can be seen in Table 4. Cycled at thirty percent of break strength, the resultant increase in number of cycles to failure is dramatic. There is still a lot of scatter in the data, however, and it is presently felt that this is traceable to rubbing problems between the Kevlar braids. A planned improvement is the addition of mylar tape between the two layers of Kevlar to eliminate any abrasion that takes place during cycling. Work is continuing on this project.

E. Conclusions

From the data on braids presented in this chapter, several conclusions can be drawn. First, braided cable is an excellent design choice for the maximum exploitation of the properties of Kevlar aramid fiber tension members. Second, the desired cable characteristics (modulus, strength, flexibility, etc.) can be generally designated by careful selection of the cable parameters (strand denier, helix angle, crimp angle, etc.). Clearly, there are other such factors which will affect the properties of any synthetic fiber cable as processing, handling and environmental conditions; however, the trends observed in this series of tests are fairly obvious. The last point to be made is that proper application of selected lubricants will increase a cable abrasion resistance; by what amount is still under question.

*The work was performed under contract at Tension Member Technology, a division of Philadelphia Resins Corporation.

Table 3. Cyclic Bend Over Sheave Cable Tests

Sample No.	No. of Cycles to Failure	Tension (KN) (% of B. S.)	Braid Lubrication
1.	1640	12.5 (20)	Dry
2.	4168	12.5 (20)	Grease
3.	1270	12.5 (20)	Grease
4.	1000	12.5 (20)	Grease
5.	186	18.7 (30)	Grease
6.	132	18.7 (30)	Grease
7.	524	18.7 (30)	Molylube
8.	756	18.7 (30)	Molylube
9.	3076	18.7 (30)	Dupont Wax
10.	2048	18.7 (30)	Dupont Wax
Phillystran open weave unjacketed 22° braid			

Table 4. Cyclic Bend Over Sheave Braid Tests

Sample No.	No. of Bends to Failure	Tension* (KN)
	30° Braid (121D)	
1.	18,640	18.7
2.	12,068	18.7
3.	2,564	18.7
4.	1,746	18.5
5.	5,306	18.7
6.	2,496	18.2
7.	2,900	18.2
	25° Braid (121CN)	
1.	13,098	18.7
2.	9,000	18.7
3.	8,064	18.7
4.	12,064	18.7

*Tension was approximately 30 percent of break strength.

Phillystran Kevlar Braid PS49S - with Nylon Jacket.
All Samples Tested on Left Sheave of Machine.

III. CONDUCTOR DEVELOPMENT

DuPont's Kevlar fiber has an elongation of 2-4 percent at break strength. When a cable is constructed of this material, the total elongation at working loads may vary from 0.5 to 1.5 percent. This factor, of course, depends on the type of cable constructed (braid, parallel or helical wrap). The elongation is greater than normally found in cable utilizing steel as strength members, but much less than the elongation found using other synthetic materials. This relatively small amount of stretch creates a problem with internally enclosed electrical conductors under cycling loads.

As the aramid strength members stretch and relax, the copper conductors must also stretch and relax. Tests to date, however, indicate that after a few initial cycles the copper quickly reaches the plastic range of deformation. Subsequently, as the tensile load on the cable is reduced, the elongated copper relaxes and goes into compression, thereby buckling the conductors. Additionally, the elongation of the cable under tensile loading induces radial forces. Repeated cycling, subjecting the conductors to these high radial stresses, causes fatigue failures.

Figure 5 is a photograph of a conductor which has suffered buckling and fatigue failure. Shown is a sample of the coaxial portion of two differently constructed Kevlar test cables (Felkel, 1976). One length of the conductor was braided with two passes of Kevlar 49 at a 23° braid angle. A second length was wrapped with two layers of contrahelically wound Kevlar 49 at a 16° angle. Individual sections of both cables were cycled in axial tension.

The braided test length had an initial permanent elongation of about 1.4 percent and an additional working elastic elongation of 1.3 percent at 50 percent of break strength. The conductor failed on the twentieth repeated tension-tension cylce (Figure 5 is a portion of that conductor). In contrast, the wrapped sample had only a 0.7 percent permanent elongation with an additional 1.0 percent elastic stretch. This also was at 50 percent of the cable's break strength, and the conductors survived little more than 100 cycles. The reduced elongation, as compared to the braid, developed because of the smaller lay angle of the wrap (16° versus 23°) and the greater tendency of a braid to squeeze the core, thereby retaining a greater percentage of its structural stretch. However, even this low stretch cable was unacceptable. These tests pointed out the urgent need for properly designed conductors for use in Kevlar reinforced cables.

The objective of the conductor development program was to determine which combination of conductor configuration and conductor material would have elastic properties similar to those of the new aramid fiber cable (Gelazis, 1976). Each conductor and its insulation required a design capable of sustaining cyclic tension, radial forces, and bending over sheaves. The approach was to choose one of two selected types of copper material, match it with one of two selected insulation materials, and form the conductors into one of four various mechanical configurations.

A. Materials

The two candidates for conductor material were tinned, soft, annealed copper and tinned Tensile Flex*. Tensile Flex is a precipitation-type alloy containing copper, cadmium and chromium, and formulated for uses requiring high tensile strength and high flex life. Conductivity is approximately 90 percent of the conductivity of pure copper. Measurements of the 0.036 cm diameter wires showed the tensile strength of the soft annealed copper to be about 207 M Pa and the tensile strength of Tensile Flex to be about 414 M Pa, both in agreement with the specifications. The conductors were insulated with two different plastic materials: thermoplastic rubber (TPR) and propylene copolymer. TPR was selected because of resilience, specific gravity of 0.88, ease of extrusion, and availability; polypropylene copolymer was selected for good past performance, specific gravity of 0.9, and hardness. These two materials will be compared in order to resolve the importance of resilience for multiconductor elastic elongation and endurance.

B. Construction

The conductors were constructed with six-tinned, 0.036 cm wires concentrically twisted around a nylon monofilament core in a tight helix. One 3048 meter sample of each conductor material was insulated with 0.036 cm wall propylene copolymer, and one 3048 meter length of each was insulated with 0.05 cm wall TPR and covered with a 0.01 cm wall nylon jacket. Each of these four basic single conductors were then assembled into singles, pairs, triads, and quads to make a total of sixteen 304.8 meter samples for this portion of the evaluation (Figure 6).

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*Registered trademark of International Wire Products Corp.

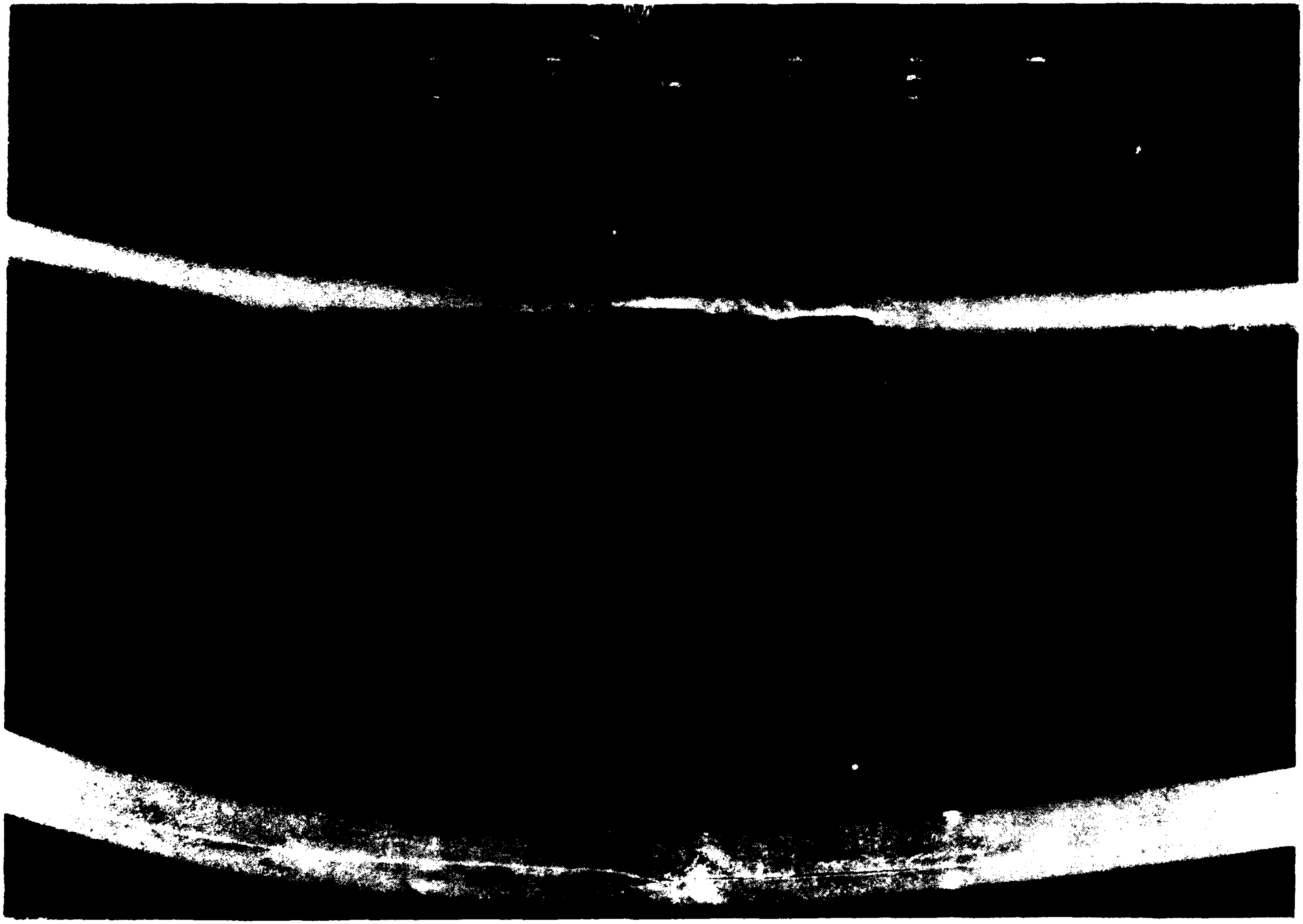

Figure 5. Combined Elastic and Plastic Elongation Effects on Standard Coaxial Core

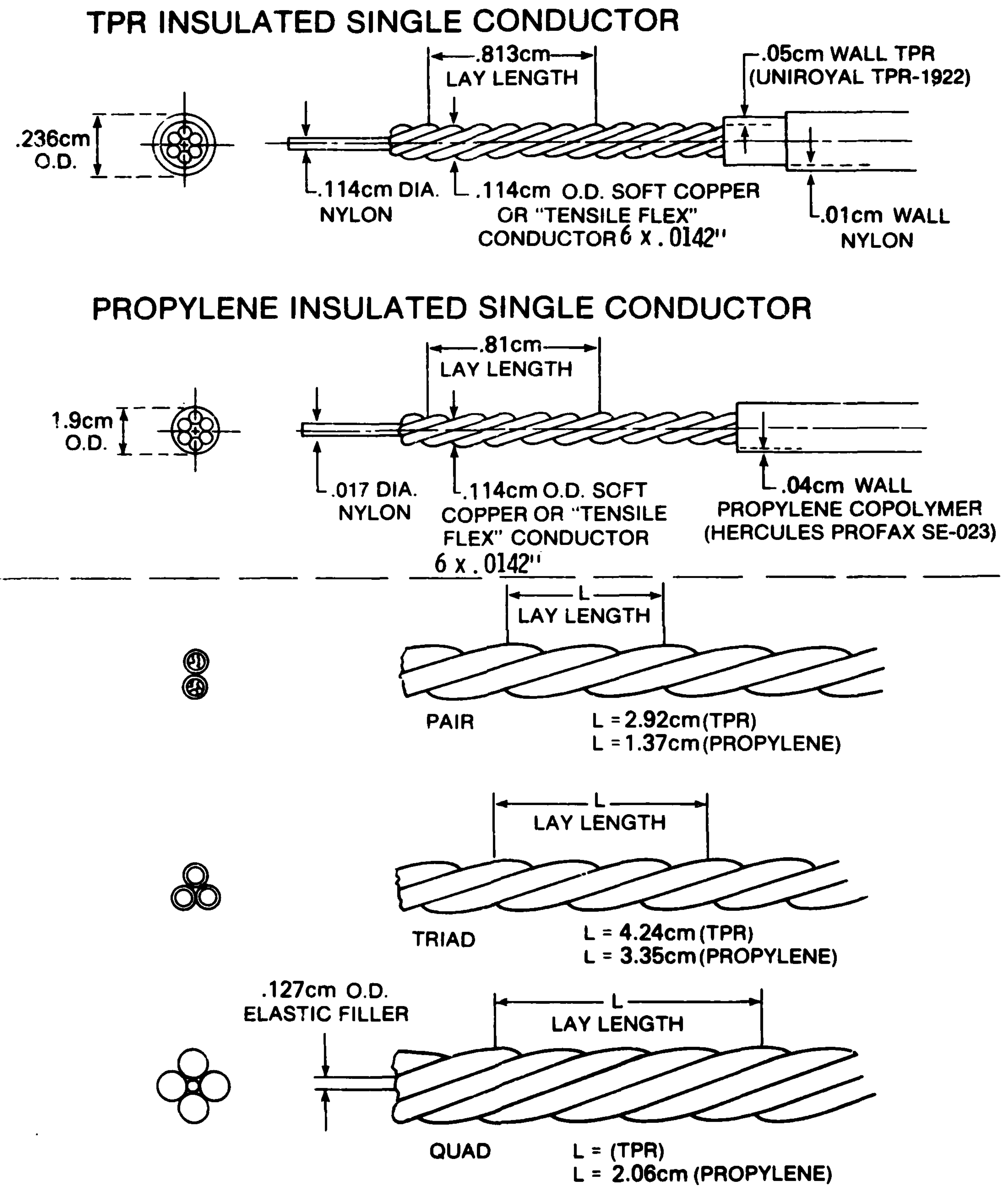

Figure 6. Construction of Conductors Used in Tension Cycling Elongation Tests

C. Testing

Before these tests began, a cyclic elongation test series on various conductors and configurations was carried out at Wall Rope. Polyester Uniline* cables were used to provide greater elongation than would be experienced by the same conductors at normal working loads in Kevlar cables. Several electromechanical cables were constructed and tested in order to pinpoint the problem areas. They were cycled in axial tension and bending.

Problems in tension-tension cycling were fairly easy to overcome for multi-conductor cables. Conductors that ran straight through a cable failed early. Conductors twisted into triads and constructed in helical paths survived many cycles to 1.5 percent elongation without failure.

Cyclic bending data, on the other hand, showed much more scatter. These data had to be qualified in regard to conductor evaluation, however, because most were for parallel-strength-member construction that placed concentrated stresses on some of the conductors during tension bending. Even so, considerable improvement was obtained by utilizing monofilament nylon cores and resilient insulation for this class of cables. At approximately 5000 cycles of double-reverse 180° bending, most of the conductors were opening, and only in the case of small braids did any conductor or cable survive 10,000 cycles; it was not clear at the time whether this was natural fatigue limit of soft copper or a function of the Kevlar elongation. Information gathered from these tests was then used to begin the final series.

1. Elongation

For single conductors, the load elongation curves are relatively independent of differences in insulation mechanical properties, and apparently represent primarily the soft copper and Tensile Flex material properties and stranding effects. The soft copper exhibits a linear (elastic) range to about 0.2 percent elongation, and Tensile Flex exhibits a linear range to about 0.3 percent elongation (Figure 7). At elongations exceeding 0.5 percent for soft copper and 0.7 percent for Tensile Flex, the conductor material is operating beyond its yield point.

Conductors assembled as pairs show a near linear load-elongation characteristic to over one percent elongation. The effect of constructional stretch is apparent in the greater linear load-elongation range for pairs when compared to single conductors. The lay length of TPR-insulated conductors assembled in pairs is twice that of paired propylene/copolymer-insulated conductors. This is a result of the larger diameter of the TPR-insulated conductors (0.05 cm wall TPR + 0.01 cm wall nylon versus 0.038 cm wall propylene copolymer). The tighter helix of the propylene-insulated pairs should provide more constructional stretch potential than the longer helix of the TPR-insulated pairs. This effect, although noted in the Tensile Flex pairs, does not hold for the soft copper pairs.

Tensile Flex triads exhibit a linear load elongation range to approximately 0.6 percent elongation - about twice that of the soft copper triads. In triads, the difference in helix lay length for the two different insulations is not as pronounced as in pairs. The lay length of propylene insulated triads is about 80 percent of the lay length of TPR-insulated triads. The reduced linear load elongation observed for triads when compared to pairs is most likely the result of the longer helix lay length of the triads. In general, the triads were assembled with the longest lay length of the 16 samples studied.

TPR-insulated quads display a larger linear range than propylene insulated quads, even though the propylene insulated quads have helix lay lengths of about 80 percent of the TPR-insulated quads. Figure 8 shows the load elongation curves of the four quad specimens.

2. Cyclic Tension and Bending

Tensile loading a conductor results in both elastic and non-elastic or permanent stretch. Elastic stretch varies directly with applied load and is the same as initial loading for subsequent loading. Permanent stretch occurs on the initial loading and generally does not occur again unless the original loading is exceeded, and then only in proportion to the excess. Permanent stretch can be a serious problem for conductors assembled into synthetic strength member cables. Conductors must elongate with the strength members of the cable; this may cause relatively large permanent stretch in the conductor elements. Upon removal of the load, as might occur in slack conditions, the conductor permanent stretch may exceed the permanent stretch of the cable. In this case, the conductors are subjected to compressive axial loading, inducing stress fatigue and possible buckling.

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*Registered trademark of Wall Rope.

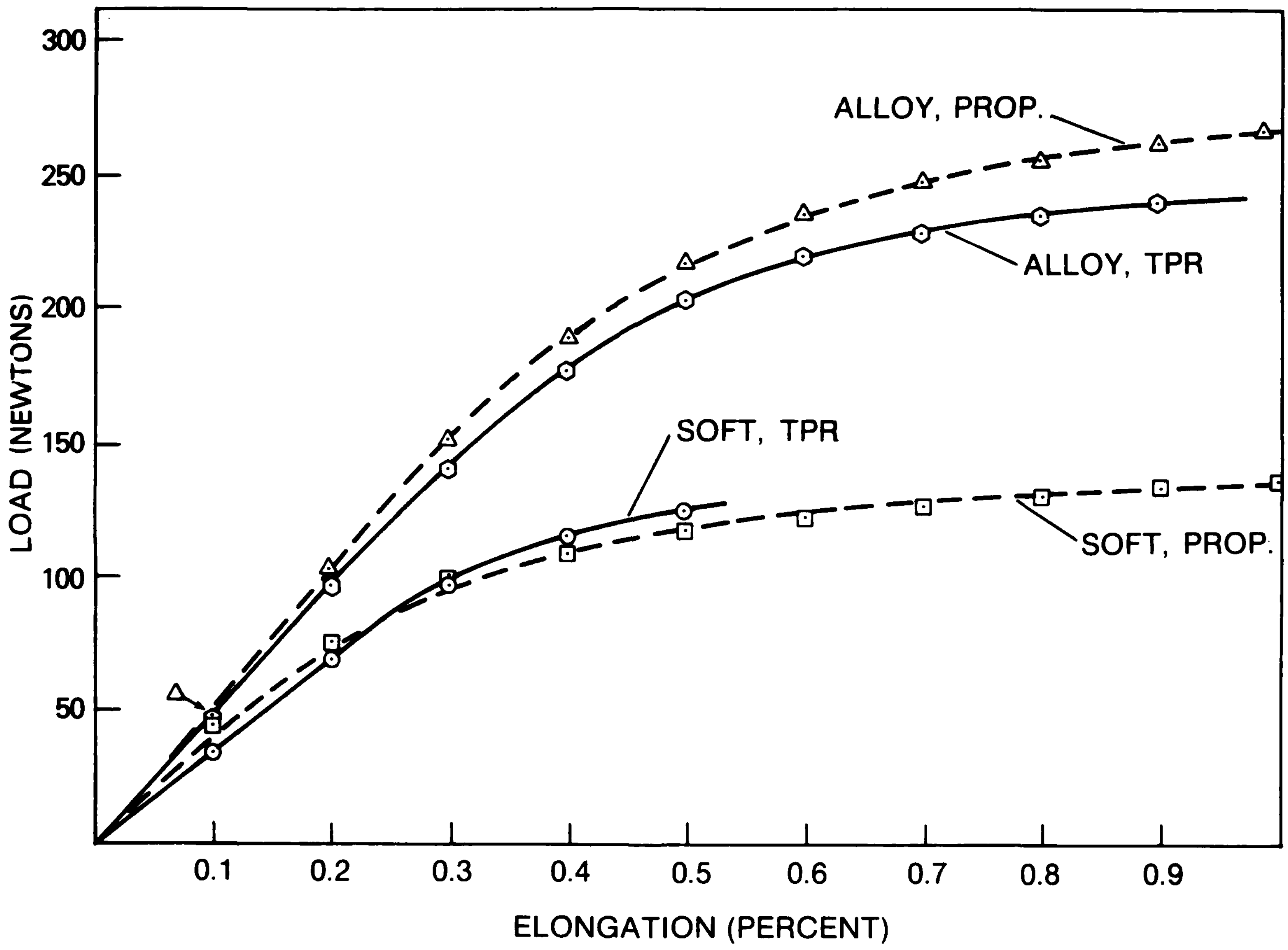


Figure 7. Load-elongation Curves for Various Test Materials (Single Conductors)

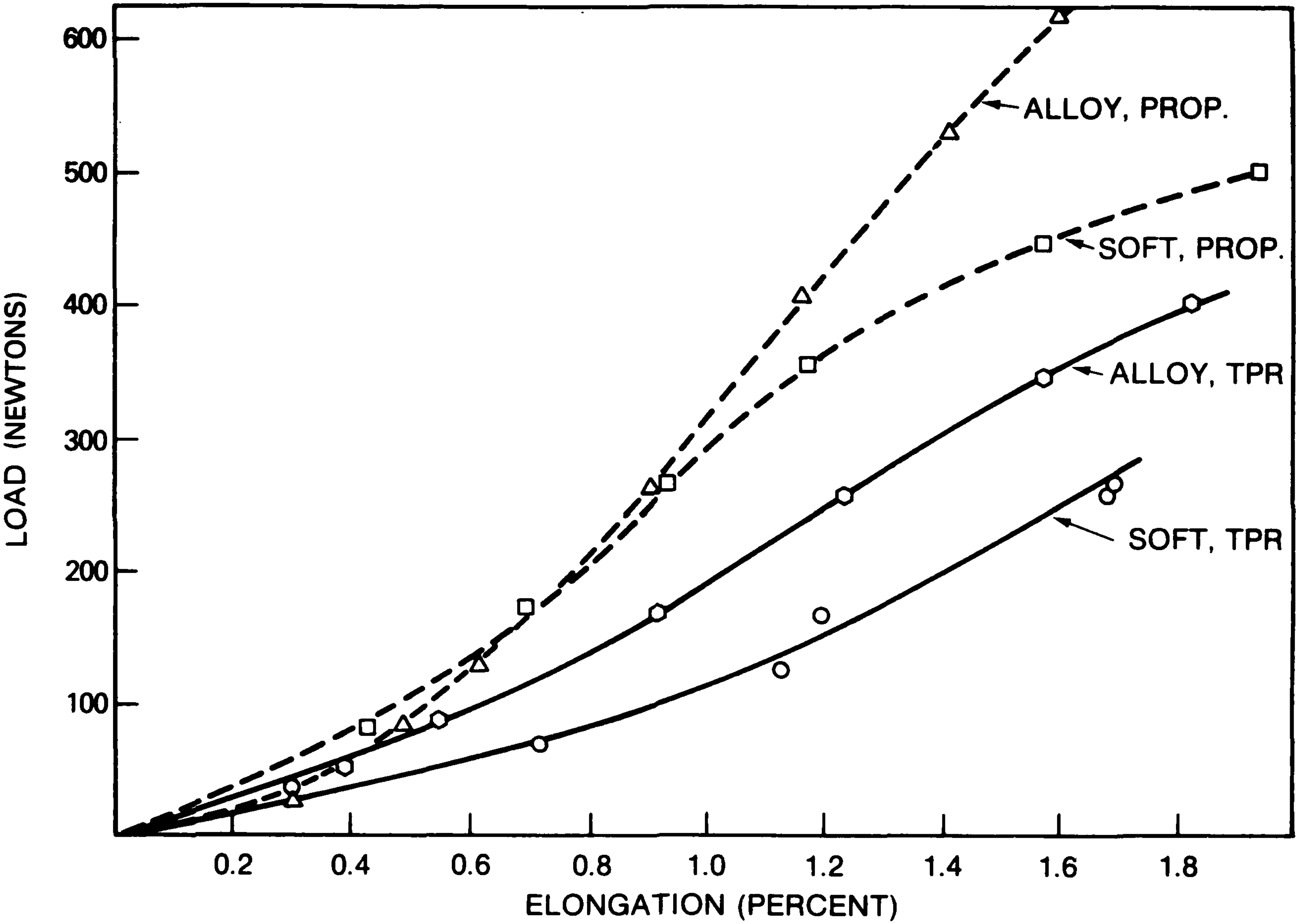


Figure 8. Load-elongation Curves for Various Test Materials (Twisted Quad Conductors)

In order to study the magnitude of the permanent elongation which occurs in the candidate conductors, samples were successively loaded and unloaded at increasing load levels and the resulting permanent elongation recorded. For example, a sample was loaded to 0.2 percent elongation, unloaded, and the permanent stretch recorded. The same sample was then loaded to 0.4 percent elongation and unloaded to determine the permanent stretch corresponding to this load condition. This procedure was continued until the permanent stretch caused by elongations of 1-2 percent were determined.

Individual conductor tests did not produce an optimum choice from the candidate designs for the electrical conductor elements. The elongation-permanent stretch characteristics were similar for all candidates with one exception: the soft, copper pair insulated with TPR showed a characteristic curve quite different from all other candidates. The elongation-permanent stretch characteristic for this pair indicated a potential for greater elongation with less permanent stretch. This result may be worthy of further investigation.

3. Composite Cable Cyclic Tension and Bending

To test the two types of copper under conditions of actual use, an electromechanical cable was constructed, consisting of a composite cable with four Kevlar braided electromechanical ropes. Two of these ropes were soft copper TPR insulated quads and two were Tensile Flex, TPR-insulated quads. These four ropes were combined in parallel with filler, and overbraided to form the core of the cable. Next, 12 triads (6 soft copper and 6 Tensile Flex) were laid in a helix surrounding the core and the entire assembly was overbraided. Figure 9 illustrates the configuration. This composite test cable also served in testing a parallel, rope-type cable used for in-line hydrophone array applications (Swenson, 1975), and a center-strength member cable with outer conductors.

Two test cable lengths were assembled and terminated by Philadelphia Resins Corporation using epoxy-potted, conical sockets. One of these samples was tested for load-elongation and cyclic axial tensile fatigue. First-cycle elongation was approximately 1.2 percent at 22.2 kn, and permanent stretch was approximately 0.4 percent (Figure 10). After 47,200 cyclic tension load cycles between 2.2 and 22.2 kn, the elongation was measured again and found to be about 1.5 percent. A final load-elongation check was performed at the end of the test, after 142,837 cycles from 2.2 to 22.2 kn and 3020 cycles from 2.2 to 31.1 kn. The total elongation was about 2 percent at 46.7 kn tensile load.

The elongation of any electromechanical cable is controlled by strength members. In this case, the resultant stretch imparted a greater load on the alloy conductors than on the soft copper conductors. In most of the cases, the alloy was loaded to almost twice the load of the soft copper. There appears to be no advantage in using the more expensive alloy material, since the alloy-rated tensile strength and published endurance limit are both approximately twice that of soft copper.

More precisely, the performance of the soft copper quads overbraided with Kevlar strength members was outstanding in cyclic tension tests. There was no failure in the soft copper quads until the cable was loaded to complete failure at the end of the test. This was surprising, since the quads in the test cable were fabricated with relatively long 6.35 cm lay length. Table 5 summarizes the results of the cyclic axial tension tests.

By noting the intersection of the elongation-permanent stretch characteristic curves with the elongation axis, a correlation with lay lengths can be developed. This data is plotted in Figure 11. Propylene-insulated conductors display a pronounced correlation with conductor lay length. Data for TPR-insulated conductors is more erratic, but tends to display a possible greater capacity for elongation without permanent stretch. In general, the tighter the helix (shorter lay length), the greater the elongation before permanent stretch occurs.

A sample of the test cable was subjected to cyclic flexing over a 91.44 cm diameter sheave at a tension of 13.3 kn. The cable passed 180° around the sheave. In this case, the configuration and location of the conductors were obviously the more dominant factors. Table 6 presents the results of the flexing. The served triad conductors outperformed the centered paralleled quads by a large margin. Obviously, the serving provides a method of preventing the unequal loading normally experienced by a cable bent around a sheave. However, the results were not conclusive in regard to the conductor material. Previous testing of individual candidate conductors over small sheaves indicated a tendency for soft copper to perform better in this mode of loading.

ELECTROMECHANICAL CABLE

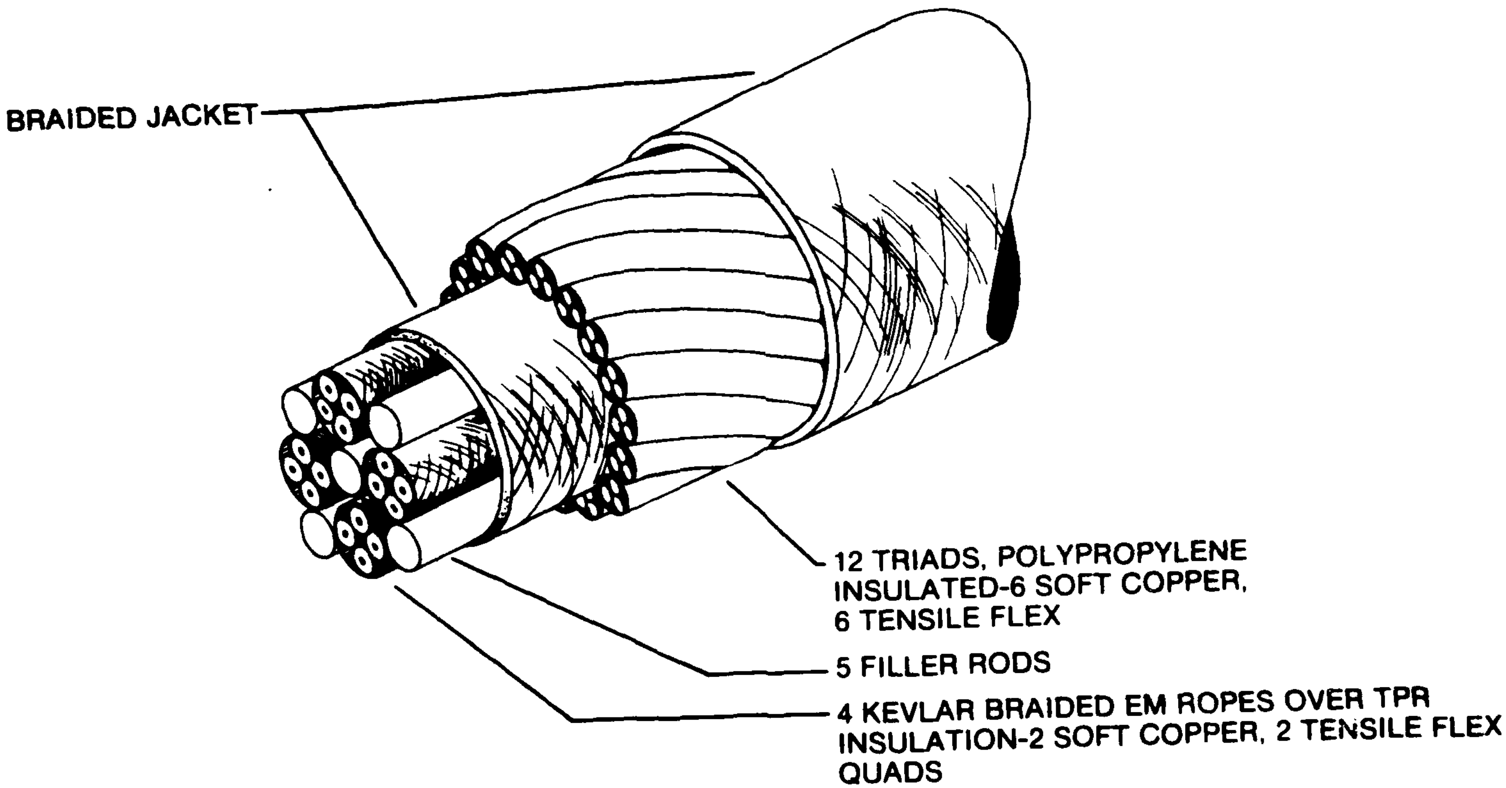


Figure 9. Composite Conductor Test Cable

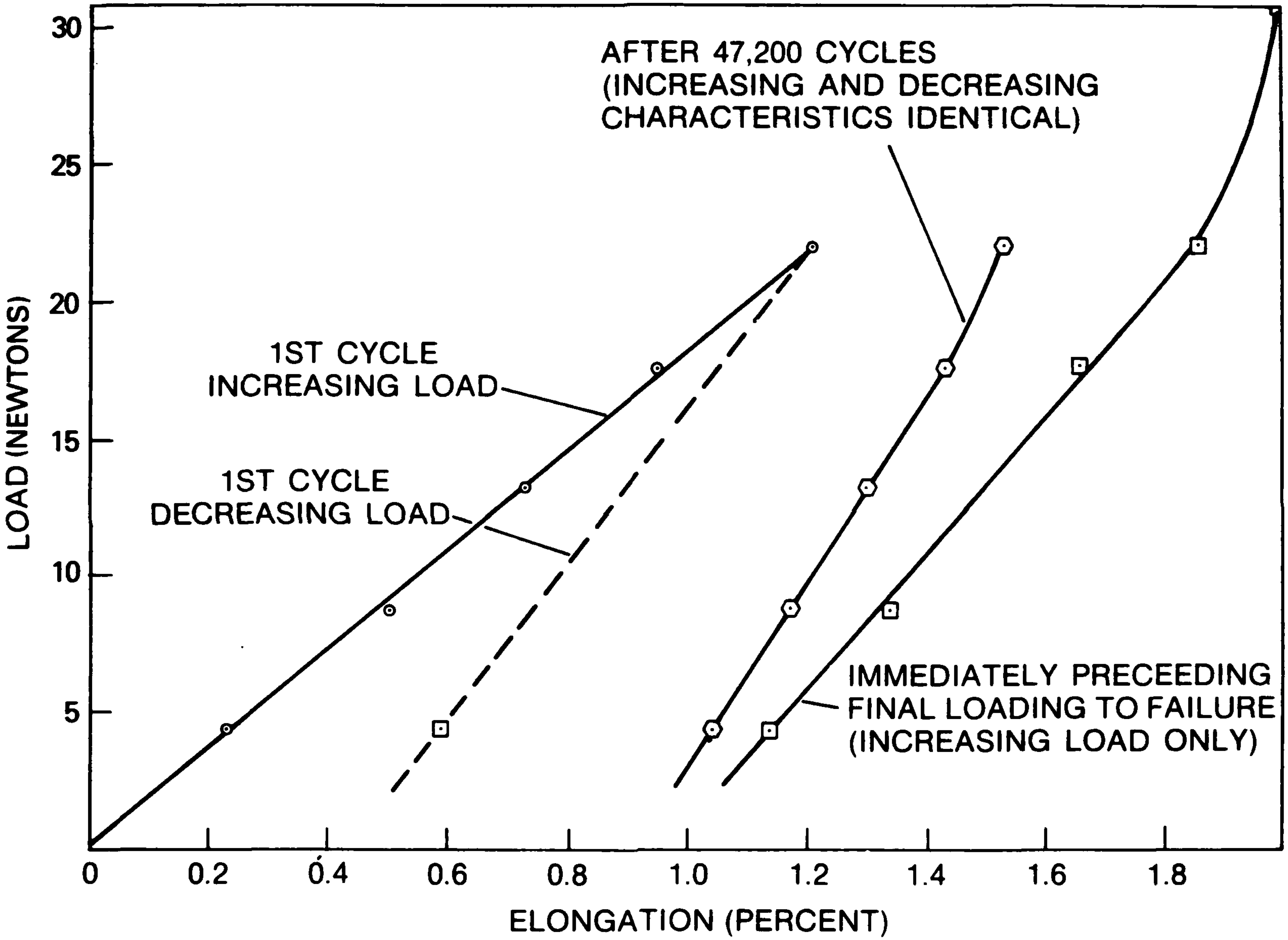


Figure 10. Load-elongation Curves for Composite Conductor Test Cable

Table 5. Cable Cyclic Axial Tension Test Results

Test Condition	Cycles	Results
Initial Cycle Elong. = 1.2%	1808	1st quad alloy wire failed
Cyclic Elong. (Max-Min) = 0.6%	5192	2nd quad alloy wire failed
Tension = 226.8 to 2268 kilograms	5882	3rd quad alloy wire failed
	6889	4th quad alloy wire failed
	10,941	5th quad alloy wire failed
	17,518	6th quad alloy wire failed
	47,198	1st triad alloy conductor failed
	47,948*	2nd triad alloy conductor failed
	81,888	3rd triad alloy conductor and 1 soft copper conductor failed prior to 81,888 cycles
	142,837	7 of the 8 quad alloy conductors were broken, 8 of the 21 triad alloy conductors were broken, and 6 of the triad soft copper conductors were broken
Load increased to 226.8 to 3175.2 kilograms after 142,837 cycles	144,630	All quad alloy conductors broken. (All quad soft copper conductors O.K.) 21 triad alloy conductors broken, 10 of 21 triad soft copper conductors broken
	145,857	Test terminated. No additional conductor breaks.
Load increased to failure of strength members		Maximum load - 4762.8 kilograms Cable failed at edge of termination.

*The continuity of all wires was continuously monitored through the first 47,948 cycles. After that, only occasional checks were conducted.

Table 6. Cable Flex Over Sheave Test Results

Test Condition	Cycles	Results
Sheave Diameter = 91.44 cm	3430	All 16 quad conductors failed between 3330 and 3430 cycles
Groove Diameter = 2.857 cm	9690	1 triad alloy conductor failed between 8734 and 9690 cycles
Tension = 1360.8 kilograms	10,783	Complete cable failure, strength members parted

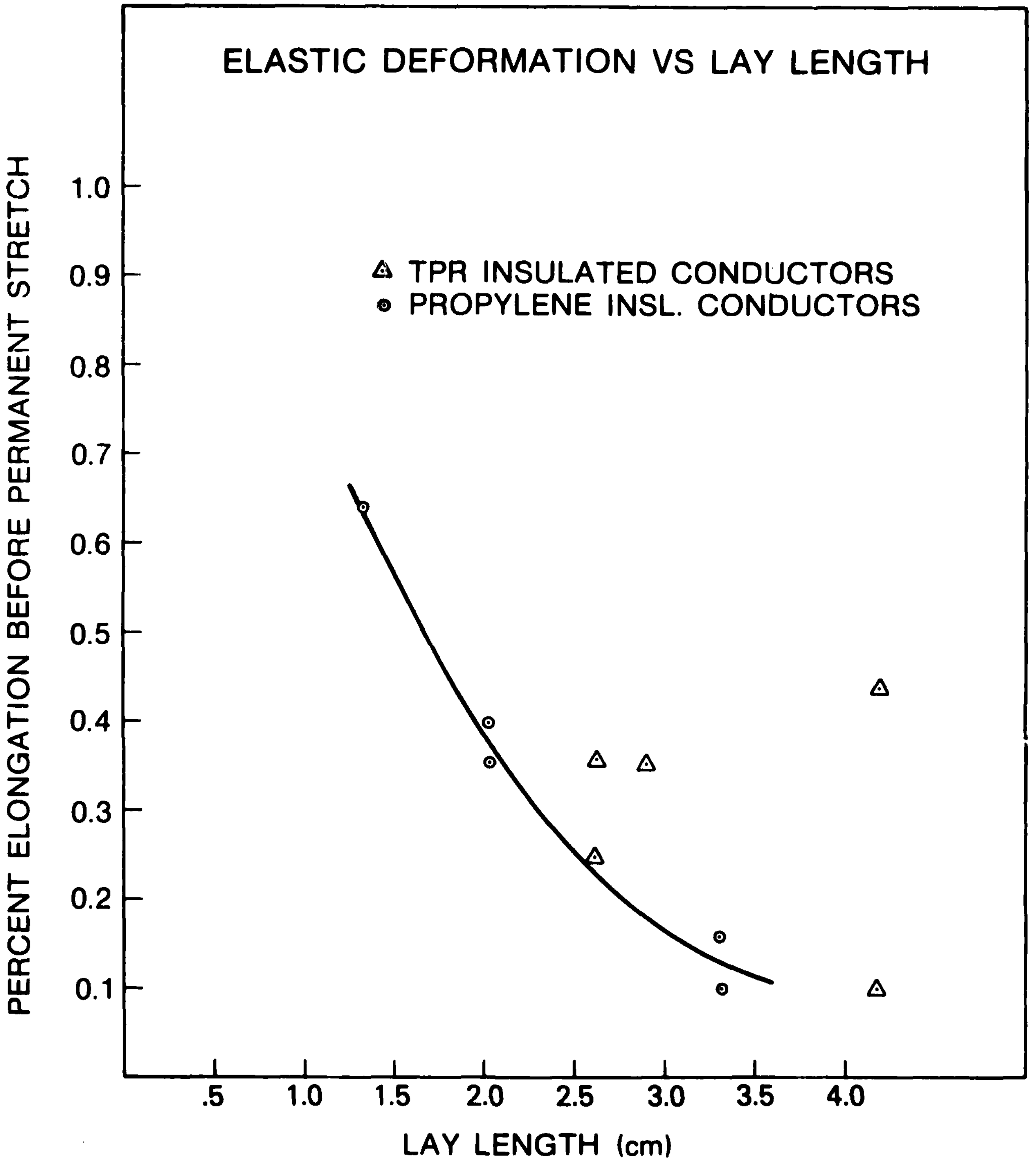


Figure 11. Elastic Deformation vs. Lay Length for Conductors with Two Different Insulations

D. Summary

This program has shown that no apparent advantage is offered by the Tensile Flex, high-strength, copper alloy over soft copper for this application. Test results also indicated that short lay lengths provided the best possibility for avoiding buckling of conductors in electromechanical cables. The short lay provides constructional stretch and extends the range of linear load-elongation for conductors.

A quad grouping of soft, annealed copper conductors overbraided with Phillystran strength members provided excellent endurance under cyclic axial tension cycling. This configuration is worthy of serious consideration for electromechanical cables where anticipated use indicates that cyclic axial tension loading will be significant.

Braided strength member cables work well with conductors because they experience a permanent stretch after elongation, which alleviates the conductor buckling problem.

Providing constructional stretch for the conductors becomes very important if an electromechanical cable is to be cycled over sheaves. This is accomplished by serving the conductors around a resilient core material in such a manner as to provide a very short lay length.

Ordinary coaxial conductor designs will fatigue in cyclic tension loading in Kevlar-reinforced cables. Special designs are required to provide constructional stretch for the center conductors. A program is being conducted to develop special coaxial Kevlar-reinforced cables.

IV. CONDUCTOR INSULATION BONDING

The ability to reliably seal any electrical conductor is of paramount importance for the successful operation of underwater instrumentation. Techniques commonly utilized to insulate conductors in cables can be divided into three general classifications: over jackets, mechanical seals, and molecularly bonded jackets.

Over-jackets completely cover the electromechanical cable; no attempt is made to seal the conductor insulation. Instead, a compatible jacket is applied over a blocked cable assembly, and bonded directly to the sensor assembly. This technique, however, is not practical for long instrumented arrays deployed in deep water because of possible local damage and hosing. Also, the possibility of water permeating the jacket under high pressure during long-term immersion exists.

Such mechanical seals as stuffing tubes, slip-on connectors, compression dams, and hand splices are, by far, the most popular in day-to-day usage because of their versatility and ease of fabrication. Generally, long, plastic-insulated conductors are sealed either by special slip-on neoprene connectors which are slightly smaller than the conductor insulation diameter, thereby producing mechanical squeeze, or by hand splicing with various types of tapes and putties. Another well-known method that has gained in popularity in the last five years is to utilize a precast polyurethane disc or grommet which has undersized holes; the conductors are drawn through the holes, which again results in a mechanical squeeze, and connected to, for example, neoprene insulated wires. The entire assembly is then overmolded with polyurethane, which bonds readily to the disc and the neoprene insulation. (Walden et al., 1973)

The third insulation technique, molecular bonding of low-density polyethylene, is by far the most reliable. However, there are few facilities available to produce high-quality molds, and when facilities are attainable, the process is expensive. The problem can be avoided by procuring special polyethylene-to-metal connectors, so that only polyethylene-to-polyethylene molds need to be fabricated during instrument assembly. These molds are generally quite expensive and require special ordering.

Despite the wide selection of insulation methods, there was a requirement for a technique that met the system requirements: ease of sensor attachment; high reliability; versatility; and low cost for multiple sensor, free flooding, electromechanical cable systems. Connectors and mechanical seals were not considered reliable for long-term exposure with many sensors gauged on common conductors. Polyethylene-to-metal bonds did not have the versatility and low cost for generalized usage and, in many cases, a metal instrument housing may not be available.

A. Tie Material Development and Testing

A different approach was therefore undertaken in which an interface or tie material was sought which could be molecularly bonded to conductor insulations (such as polyethylene, polypropylene, TPR, and EPR) and, at the same time, to neoprene, during one simple vulcanizing operation. Neoprene is an obvious choice because it interfaces very well with itself, metals, and polyurethane; which are the materials used with either pressure- or nonpressure-protective electronics. In addition, once neoprene can be utilized for an interface, all commercial connectors become easily usable; and, since many facilities can vulcanize neoprene, field-repair operations become feasible. Finally, neoprene provides small molds with flexible, nonstress-sensitive lead required for miniaturization of the sensor package.

Discussions with the engineering staff at DeBell and Richardson, Hazardville, Connecticut, indicated that the preceding approach might be feasible by using a special blend of Ethylene Propylene Diene Monomer Rubber (EPDM) as the interface or tie material. This led to a two-year Office of Naval Research (ONR) funded program called Materials Bonding (Final Report, 1975).

The program proceeded in three phases. The first phase consisted of an investigation of various potential EPDM formulations and curing systems for future bonding studies. As a result of this evaluation, a formulation (no. 44) was selected that met the desired physical properties over a suitable curing temperature range and time. This was followed by a second phase in which the bonding strength of the standard compound was measured by 90° peel testing on substrates of polypropylene, polyethylene, neoprene, stainless steel, and beryllium copper. Improvements were made to the formulation in the third phase, which was concluded by actual insulated electrical conductor molding and pressure testing. Again, the EPDM tie material was successfully used between neoprene, polypropylene, polyethylene, and neoprene. Table 7 lists the properties determined on compression molded ASTM specimens conditioned at 23° C and 50 percent RH for 16 hours after molding.

Table 7. Formulated Compound Properties

Compound Properties - General

Specific Gravity ASTM-D742	.9946 at 23/23°C
Water Absorption ASTM-D570	.141 percent in 24 Hours
Water Vapor Transmission ASTM-E96 Condition E	5.8 gm-mils/100 in^2/24 Hours

Compound Properties - Physical

	Cure Cycle	
	320° F 30 min.	240° F 60 min.
Tensile Strength	10.39 M Pa	7.65 M Pa
Ultimate Elongation	340%	560%
Modulus 100%	370 psi	250 psi
Modulus 200%	750 psi	380 psi
Modulus 300%	1310 psi	560 psi
Hardness Shore "A" ASTM-D2240-68	68/66	65/60

Compound Properties - Electrical

		Conditioning	
		48 Hours 23°C and **50% RH**	24 Hours 23°C **In Water**
Dielectric Strength ASTM-D149		370 volts/mil	350 volts/mil
Volume Resistivity ASTM-D257		10 x 10^{15}-cm	4 x 10^{15}-cm
Dielectric Constant			
ASTM-D150	10^2 Hz	4.68	4.75
	10^3 Hz	4.56	4.64
	10^6 Hz	4.22	4.28
Dissipation Factor			
ASTM-D150	10^2 Hz	.0178	.0170
	10^3 Hz	.0153	.0160
	10^6 Hz	.0256	.0264

In the last phase of this program, funded by NAVFAC, the various insulation materials employed in the conductor development program were molded to the tie material and pressure tested (Redding, 1976). The substrate material preparation techniques, cure times, and cure temperatures were taken from the previously referenced report. This work was directed toward determining if the selected tie material would be as effective under relatively long-term hydrostatic pressure as under short term testing.

The wire insulating materials included:

1. **Polypropylene Copolymer** (PP), crystalline propylene/ethylene copolymer.
2. **Polyethylene** (PE), low density, high molecular weight resin developed for underwater cables.
3. **Thermoplastic Rubber** (TPR), low density flexible polyolefin; processes like a thermoplastic, but has physical properties of rubber.
4. **Ethylene Propylene Diene Monomer Rubber** (EPDM), thermosetting hydrocarbon elastomer having chemical building blocks in common with polyethylene and polypropylene; physical properties similar to neoprene; chemically similar to EPR, but having two bonds instead of just one.
5. **Neoprene** (N), elastomeric compound commonly used as a jacketing material on many commercial cables and electrical terminations.

B. Conductor Sample Description and Preparation

Surface preparation of all substrates prior to molding is an important first step in the bonding process. Preparation methods are classified as either chemical or mechanical. Chemical means are used in many cases to both clean and activate a substrate prior to bonding, but require careful control. Mechanical methods involve surface removal by roughening with abrasives, in addition to solvent cleaning. This process is satisfactory and equally applicable to either laboratory or field application. Surface roughness as a result of treatment is normally a plus factor, since it permits a degree of mechanical bonding in reinforcement of chemical bonding achieved. Due to rapid formation of oxide films and the presence of airborne contamination, it is important that the surface preparation be done immediately prior to the next operation — either molding or further treatment.

When used, the application of coats of either primer or adhesive by brush should be a "flow on" rather than a "brush out" process. Dip or spray application is even more effective.

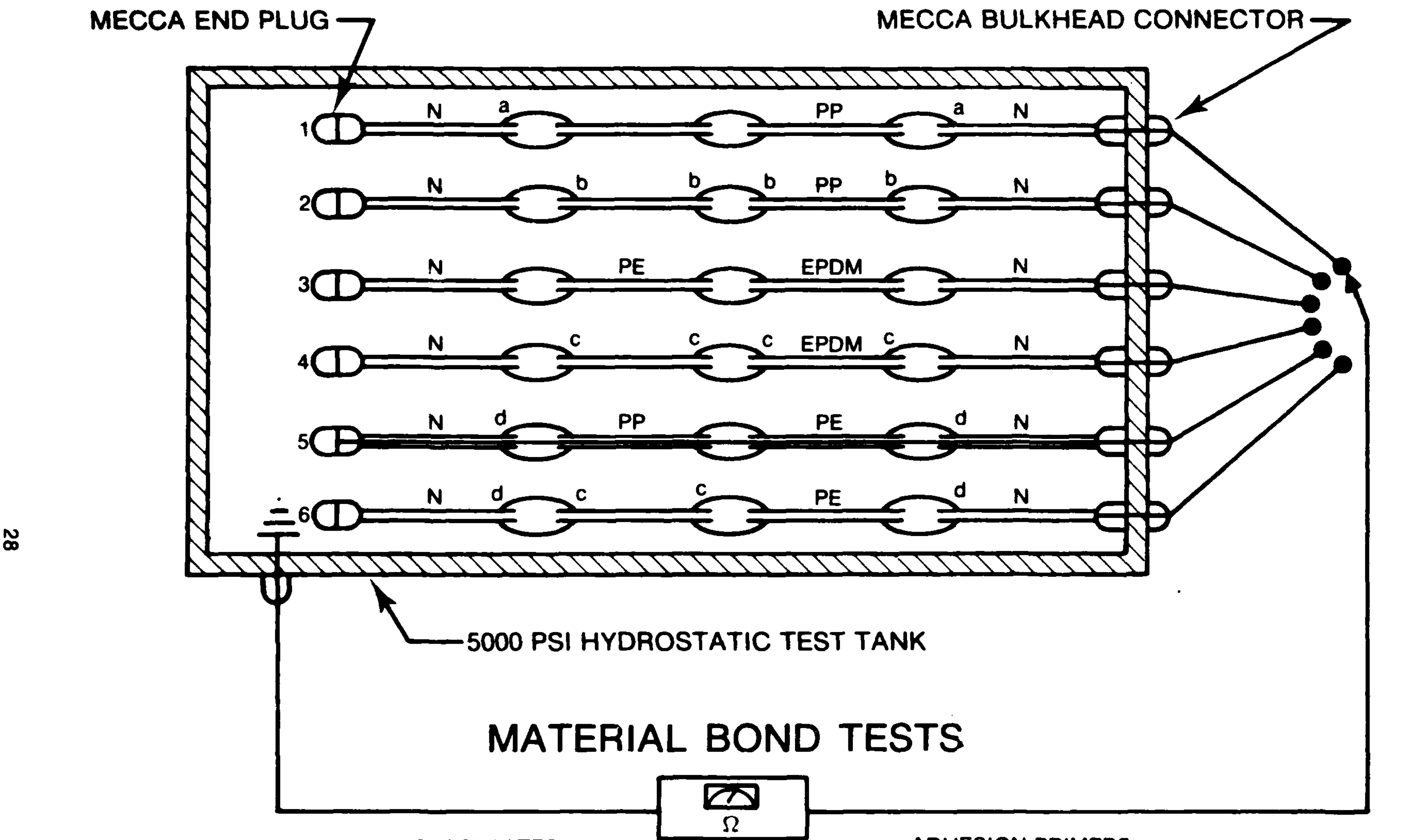
A short length of each sample cable was prepared for testing. The insulation material was roughened, solvent cleaned, and, in some cases, primered. A schematic diagram of the various combinations of wire insulating material, adhesion primers, and EPDM splices is shown in Figure 12. A more complete description of the methods and materials used to treat the substrates prior to bonding, as well as the bonding techniques, can be found in Reference 2. The cables were then electrically spliced, compression molded with the EPDM compound, and cured.

C. Pressure Testing

The completed samples were electrically tested. A megger was used to measure the voltage drop of each multiple cable before and after immersion. All voltage drop readings were taken at 250 VDC after 30 seconds of electrification. The test cables were installed in the hydrostatic tank, and pressurized 34.47 M Pa. Each day, the pressure was cycled briefly from the normal load of 34.47 M Pa to zero load, and back again to 34.47 M Pa, and a reading was taken once a week at the three points.

These tests continued for about two months with two failures out of the six cables; neither were caused by a bad splice (J. J. Redding, personal comment). Cable #2 had very low readings because the adhesion primer used was conductive. After dipping the insulation into the primer, the dried primer was not completely covered by the EPDM mold; consequently, a direct electrical path existed between the wire and the water. Primer b was omitted, but it was also apparent that in future splices, the molding compound should lap over the primered area to avoid this problem. Cable #4 also developed a short, but this was caused by thin TPR insulation on one sample which cracked under pressure cycling. Both multiple cables were completely redone and retested, and proved to be as successful as the other four.

That EPDM formulation will bond well to various treated substrates and develop sufficient adhesion to qualify as a tie material can be concluded from all results obtained prior to the hydrostatic tests. The hydrostatic tests show the material to be a good choice for underwater cable splicing and termination.



SUBSTRATES

TPR	THERMOPLASTIC RUBBER
PP	POLYPROPYLENE
PE	POLYETHYLENE
EPDM	ETHYLENE PROPYLENE DIENE MONOMER
N	NEOPRENE

ADHESION PRIMERS

a	OSN-1/AP 1598
b	AP 1645/66
c	AP 1598
d	NM-2/AP1598

Figure 12. Schematic Diagram of Various Combinations of Insulating Materials, Primers and Substrates in Pressure Test Tank

V. SEA EXPERIENCE SUMMARY

A. Woods Hole Oceanographic Institute

1. Buoy Farm

In February 1974, Woods Hole Oceanographic Institution (WHOI) deployed two shallow-water test moorings (Figure 13) (Walden, 1976). Both consisted of approximately 53380 newton break strength, 1.02 cm diameter Wall Rope Uniline. The moorings were statically loaded to 680 kilograms, and to much higher loads under dynamic wave action (Table 8).

The first line failed, apparently due to a cut, after 26 months. The buoy and upper section of the rope sample were recovered on a nearby beach. Subsequent information from WHOI reported that testing of the recovered rope indicated a deterioration of Kevlar in sea water (Walden, 1976). Both Wall Rope and DuPont obtained samples of the rope. Several 1550 denier yarns and 36,000 denier strands were removed from the rope and tested. The major conclusion was that sufficient strength remained in the rope and should not have failed during normal usage. Residual yarn strength was nearly 80 percent of the original strength. What strength loss occurred when the rope was awash on the beach was hard to assess.

The second buoy and mooring line was recovered in May 1976, after 29 months. Tensile strengths of the yarns and strands removed from this rope were high. The average break strength of the material was well within the release limits of virgin yarn shipped from DuPont as first-grade fiber. The rope manufacturer found a strength reduction when testing samples of the rope. The tensile test results of sections from the recovered rope and eye spliced end fitting were slightly harder to assess. The original break strength of the rope was estimated to be 53.4 kilonewtons, but was never verified. Tests of the recovered rope specimens produced an average break strength of 43460 newtons. On the basis that there was little strength loss in the individual fibers, this value is probably more representative of the original rope break strength than the projected value. The spliced end fitting which sustained, along with the rope, an estimated ten million tension-tension cycles from wave action, broke at a test load of 36475 newtons. This is only about 15 percent less strength than the rope. If this end fitting was removed and a new splice put in, the conclusion was that this line could be redeployed as well as a new line.

2. Current Meter Strings

Two different constructions of Kevlar parallel rope were purchased, each from a different manufacturer, to be tested in deep-water subsurface moorings by WHOI (Walden, 1976). The first was a Wall Rope 0.64 cm, 26690 newton average Break Strength (BS) rope of Uniline construction, made with 17 slightly twisted parallel fiber yarns, and covered with neoprene coating. This was jacketed with Dacron braid for protection. The second was manufactured by Columbian Rope, and was also a 0.64 cm, 26690 newton BS rope with 14 slightly twisted parallel fiber yarns, covered with a 0.76 cm polyethylene sheath. The Columbian rope, however, was built of standard finish rather than the rope finished Kevlar utilized by Wall. Four samples of each rope were tested prior to use. The Columbian rope had an average BS of 30090 newton; the Wall Rope averaged 29660 newton BS. All breaks were midspan.

Subsurface moorings of each rope were deployed on a station located east of Bermuda. The tension in all four legs was 4540 newtons, or about 17 percent of the ropes' BS. Eight months laters, they were recovered, samples taken from each rope, and then redeployed in a new configuration. Two new moorings were set using the same rope samples; however, each contained sections of both rope types. One of the moorings was installed at about 33 percent of the BS, the other at roughly 45 percent of BS. The recovery occurred after four and three months, respectively. Upon recovery, the ropes suffered considerable entanglement in hardware. Visual evidence of damage to the polyethylene sheath and none to the Dacron braided jacket was noted.

Table 8 provides a listing of the average break strength of the two ropes at various stages of use. The uncoated standard finish fibers of the Columbian rope apparently suffered greater internal self-abrasion, in addition to being more vulnerable to external damage for lack of a tough jacket. After studying the fibers and strands of the two ropes, conclusions are that a 10 percent strength reduction of rope tensioned to 33 percent of BS is a reasonable figure. However, this reduction is probably due to abrasion caused by the fibers working on each other rather than degradation of the material in the sea water. Section D of Chapter X describes laboratory tests which dispel any doubts about this.

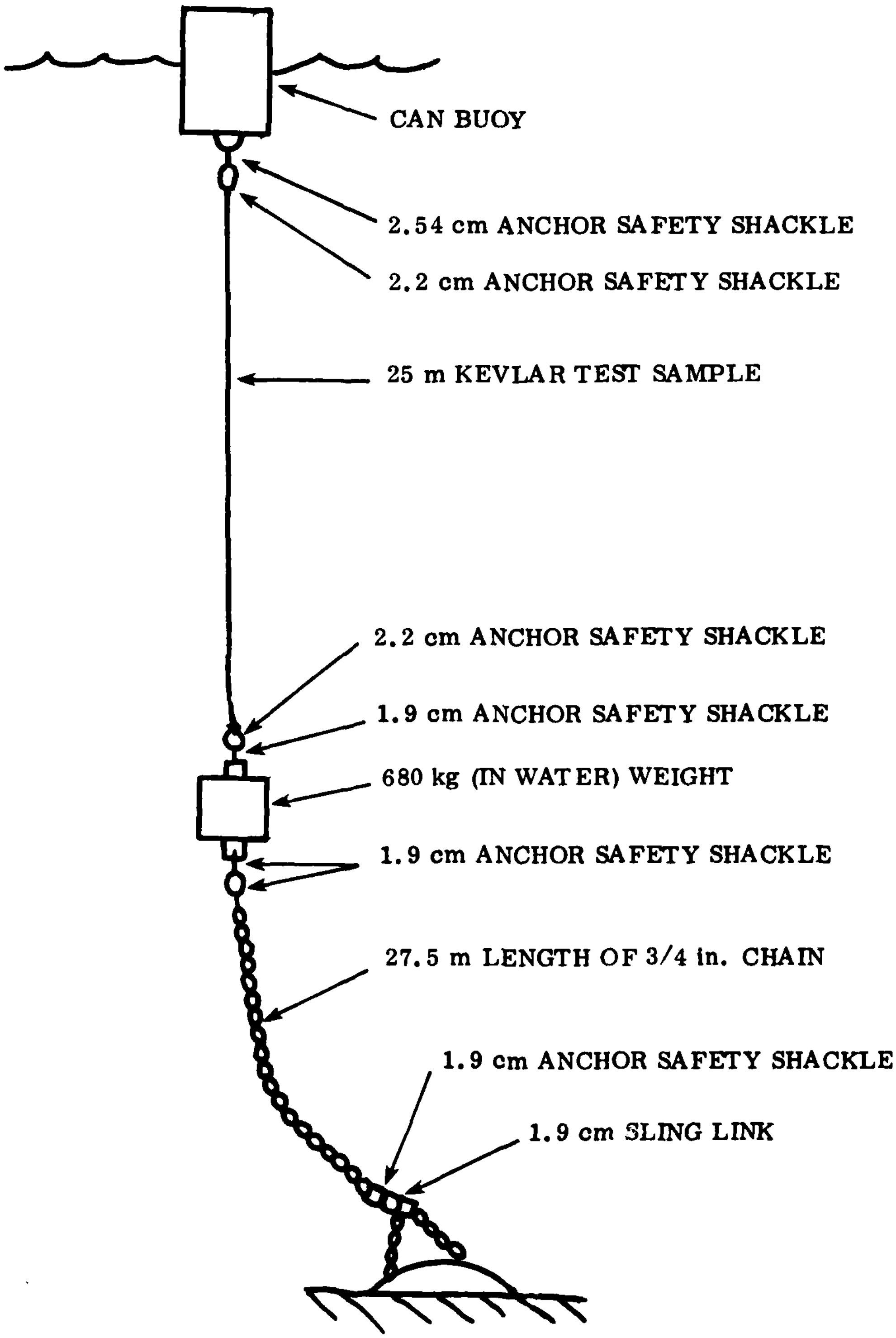


Figure 13. Configuration of Shallow Water Test Buoys

Table 8. Loss of Strength at Various Loading Conditions and Exposure Time

	Initial Breaking Strength N	18 mos. at 17% BS		8 mos. at 17% BS plus 4 mos. at 33 % BS		8 mos. at 17% BS plus 3 mos. at 45% BS	
		N	% loss	N	% loss	N	% loss
WALL ROPE - UNILINE							
Complete Rope (WHOI Data)	29660	28400	4	26720	10	24475	17
Yarn Strength (DuPont Data)	1950					1860	5
Yarn Strength (Wall Data)	1950					1790	8
Complete Rope (Wall Data)	29290	28690	2			25220	14
COLUMBIAN ROPE							
Complete Rope (WHOI Data)	30100	25730	14	22740	24	20630	31
Yarn Strength	2575					1855	28
Complete Rope	30740	29270	5	26600	13	22400	27

*High Variability, 162.39-260-8 kilograms

B. Mobile Acoustic Range Buoy

In response to a need for a lightweight, easily deployable buoy having the ability to collect and transmit real-time acoustic data, NUSC developed a two-stage, self-mooring system (Bourgault, 1976). The surface buoy provided a lightweight platform which supported an RF telemetry transmitter and antenna. Buoy-to-sensor coupling was provided by a braided Kevlar electromechanical cable. This cable was, in turn, connected to the anchor by a series of small plastic trim floats attached to the cable near the surface. Sensor support was provided by a series of syntactic line floats attached to the cable near the subsurface sensors. Figure 14 depicts the mooring configuration.

A braided aramid fiber rope construction was chosen for several reasons.

1. The cable had to be lightweight and torque free.
2. Electrical conductors were relatively protected within the jacketed core of the cable.
3. The braided cable was easily terminated in the epoxy-filled clevis.

The cables were manufactured by Philadelphia Resins Corporation.

The electromechanical cable composition began with a core of nylon filler rod. Around this core, six stranded polypropylene-insulated electrical conductors were wrapped with a high helix to ensure compliancy. Surrounding the conductors was a wrap of mylar tape which both protected the conductors and provided a smooth bedding surface for the Kevlar. Next, two layers of Phillystran PS29 B45 braid were applied in order to attain the desired breaking strength of 20 kn. Finally, a layer of polyurethane was extruded over the braid to provide abrasion protection and reduce the possibility of damage from fishbite. Completed cable diameter was 1.12 cm.

The mechanical cable consisted of three layers of Phillystran braid over a nylon filler rod, with an extruded polyurethane outer jacket. Cable diameter in this case was 0.635 cm with a designated minimum break strength of 18.15 kn.

The preeminence of the choice of aramid fiber tension members over steel first became evident during deployment. The mooring was streamed aft of the ship in a 3 sea-state with zero tension, which eliminated many hazards inherent in deploying heavy systems. The torque-free construction made it possible to transfer loads and attach instrumentation without kinking problems normally associated with wire ropes. Recovery of the system was accomplished as easily as the deployment.

Visual inspection of the cables after four months showed:

1. Little to no biological growth on the polyurethane jacket.
2. No evidence of fishbite.
3. The outer jacket provided excellent abrasion resistance at chafing points.
4. A series of tensile tests on samples before and after deployment show a marked decrease in cable strength.

This last item, along with other similar reports, caused much concern and was part of the impetus behind the wet tension fatigue tests (Chapter IX, Section D). Table 9 summarizes the results of the tests; three samples of each cable were tested prior to use, and three after. Both the mechanical and the electromechanical cable showed a marked decrease in break strength. Because of experience gained in the NAVSEA coaxial cable program, it is speculated that the reduction in strength was caused by the layers of Kevlar abrading on each other.

C. Project ANZUS Eddy

An international experiment called Project ANZUS (Australia, New Zealand, United States) Eddy was conducted in March 1975 to study the mesoscale ocean eddies. The aim was to detect ocean eddies off the east coast of Australia using satellite, aircraft, and surface ships, and to study the oceanographic properties of the eddies, particularly the acoustic characteristics. (Scully-Power, et al., 1975)

An easily deployable, vertical line array of hydrophones, suspended from the surface to a depth of 450 m, was required for the acoustic phase of this project. Fabrication of the cable's tension members required lightweight, compliant, noncorrosive and completely torque free design, which was accomplished by the use of Kevlar parallel-fiber Uniline. This unique layout allowed the in-line hydrophones to be inserted into the cable without cutting the load bearing strands or interfering with other conductors. The resulting 1.9 cm O.D. cable had six triads of electrical conductors, a break strength of 66.72 newtons and weight of approximately

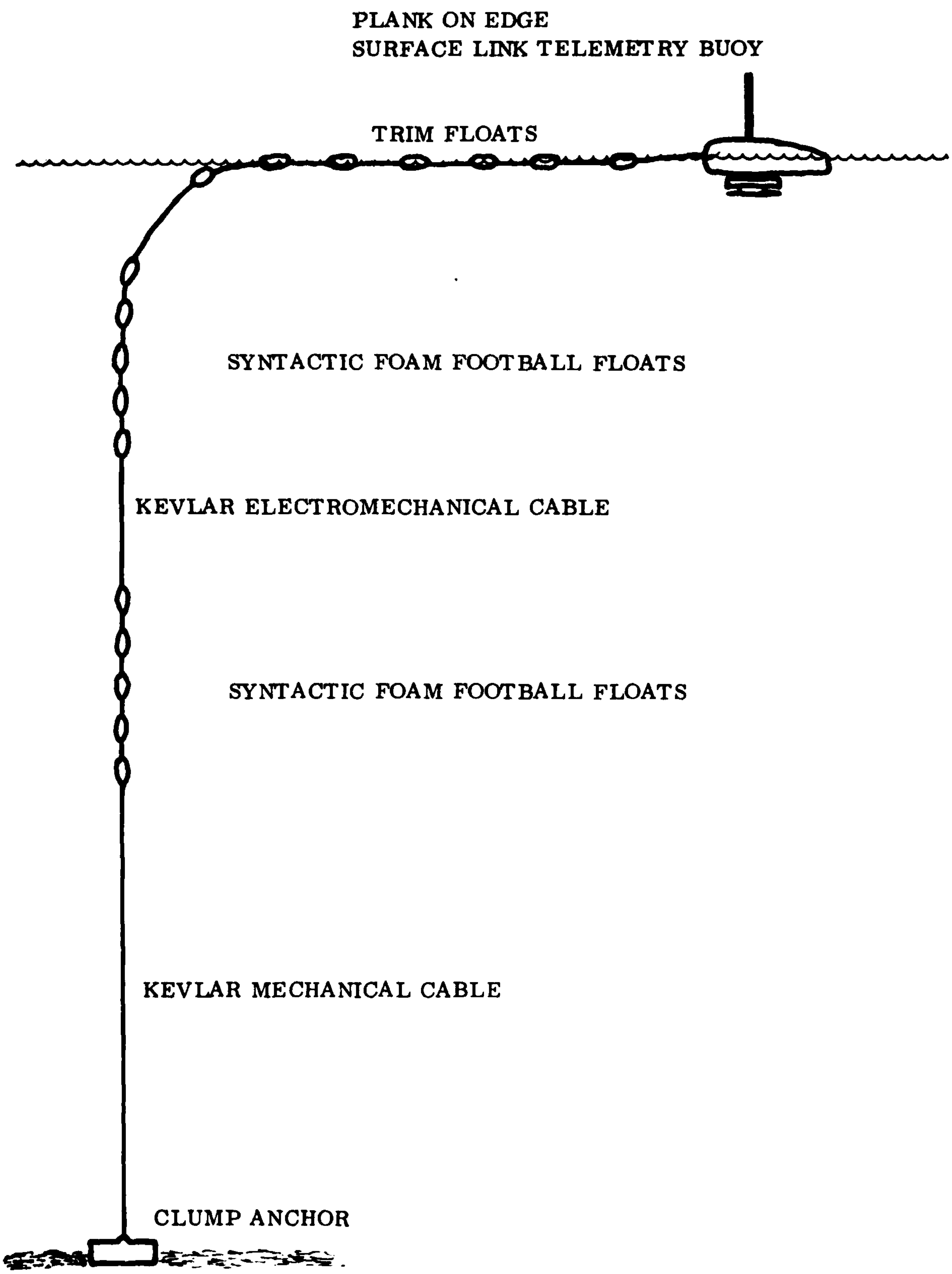


Figure 14. Mobile Acoustic Tracking Range Buoy

27.2 kilograms per 34.5 meters and was nearly neutrally buoyant in sea water. In addition, the cable had hair fairing woven into the outer jacket during construction to reduce cable strumming and associated acoustic noise. The array was suspended in the configuration shown in Figure 15. Distributed-buoyancy, surface suspension technique to decouple the wave action from the array was utilized (Scully-Power, 1973). This system provided an excellent low noise acoustic sensor array.

The array cable previously used in the Mediterranean in both vertical and "on-the-bottom" deployments was coiled in a box and flown to Australia from the U.S. At Sidney, the hydrophones were inserted in desired locations, the array was water tested alongside a harbor pier, and then transferred in a box to the deployment vessel. On site, the array was deployed by hand. This procedure was repeated at three sites in weather ranging from sea-state 3 to sea-state 4.

The reusability, noncorrosiveness, ease of transportation and array assembly/deployment were clearly demonstrated in this early usage of a Kevlar array. The net result was a low-cost experiment, reliably carried out on the other side of the world, which produced good quality data under rigorous conditions. Upon completion of the experiment, the array was reboxed, flown back to the U.S., and subsequently used in a similar deployment mode in the North Atlantic near Norway.

Table 9. Kevlar Cable Tensile Tests

BREAK STRENGTH (In Newtons)		Static Mooring Load (% of BS)	Average Decrease In Strength (%)
Before Deployment	After Deployment		
E.M. Cable			
1. 24690	19350		
2. 26690	20020	10	
3. 26690	20020		
4. ----	19130		
5. ----	20260		
Avg. 26020	19750		24%
M. Cable			
1. 19350	15010		
2. 20680	16010		
3. 20020	16010	12	
4. ----	14690		
5. ----	15120		
Avg. 20020	15370		23%

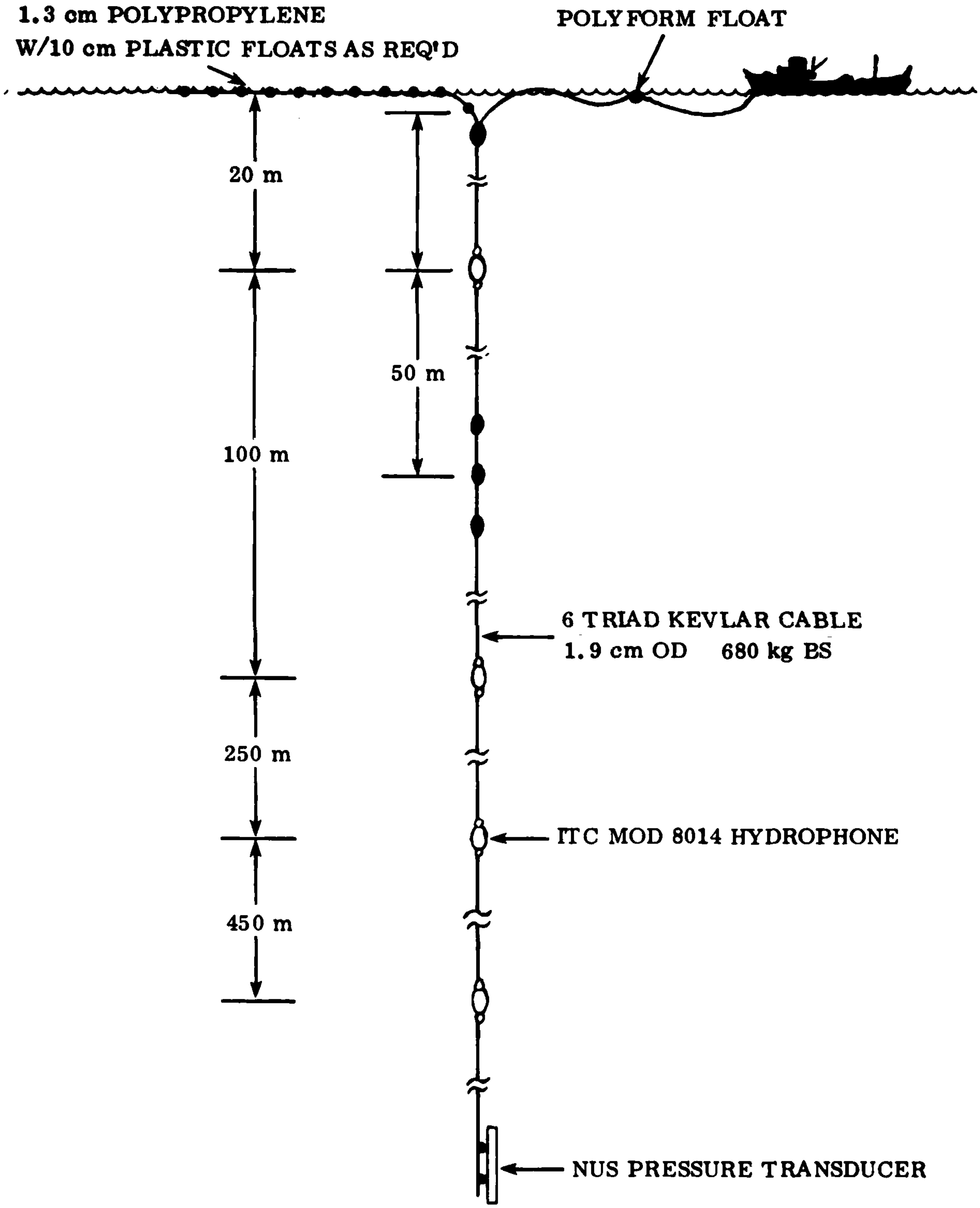


Figure 15. ANZUS Eddy Acoustic Array.

VI. SUSPENDED KEVLAR ARRAY TECHNOLOGY EVALUATION

A. Background

In 1970, NAVFAC sponsored a five year program called the "Cable Development Program for Suspended Applications" (Swenson, 1975). This program investigated such aspects of suspended array technology as analysis, load bearing materials, conductors, insulation sealing, cable construction, sensor mounting, assembly, testing, fairing, cost, etc. The principal thrust was in development of Kevlar mechanical and electromechanical cables; however, it always imposed the system implications of suspended arrays on their designs. Over the five-year period, the program produced many tests and several reports and papers. However, the most convincing evidence of utility of new Kevlar technology was actual utilization of the new cables at sea. This was generally accomplished by integrating the new designs into ongoing sea measurement programs at little or no cost to the host program. The most significant of these programs was the Long Range Acoustic Propagation Program (LRAPP) (King et al., 1973) in which the Moored Acoustic Buoy System (MABS) (King et al., 1977) was retrofitted with several long Kevlar arrays. Thus, Kevlar cables have been deployed numerously in various configurations in many parts of the world's oceans (Figure 16).

At the end of FY 75, the Cable Development Program for Suspended Sensor Applications was completed, and had demonstrated the feasibility of Kevlar cables by laboratory and sea tests. In addition, industry was spurred into providing these cables on a production and competitive basis. At the completion of the new program, new technology was to be utilized in a major sea experiment which thoroughly exercised its acclaimed higher performance, reliability, and versatility at lower cost.

B. South Pacific Ambient Noise-3 (SPAN-3)

The opportunity to strenuously test the new technology was presented during the U.S. participation in the SPAN-3 experiment in March and April 1976. This joint U.S./New Zealand experiment's major objective was to measure the ambient noise in a quiet (minimal shipping) ocean basin north of New Zealand, and to evaluate a totally Kevlar array and mooring system in both vertical and horizontal deployments.

Technically, the challenge was to prepare the MABS equipment, procure the additional mooring components, ship the equipment to the other side of the world, assemble it in the field, and deploy it from a single screw ship manned with a military crew unfamiliar with this type of equipment in questionable weather, within six months from start and with a $100k budget. In addition, a high degree of reliability was required due to the large expenditure of ship and aircraft time, plus expendable experimental equipment provided by New Zealand.

1. Experiment Description

The self-recording subsurface MABS system, equipped with a 1830 meter long array, was deployed in the vertical mode at point "A" (Figure 17) in 4250 meters of water within the South Fiji Basin to measure the ambient noise at various depths. Two east-west aircraft flights were conducted dropping AXBT and SUS shots to determine acoustic propagation anomalies at the perimeter of the basin. These regions are dominated by extensive ridge systems which may affect the ambient noise contribution due to distant shipping. The SUS shots were detonated every 15 km (total of 110 shots) and 20 AXBT buoys were expended. A third aircraft run was north-south and was designed to study general in-basin acoustic propagation necessary to the modeling of ambient noise. An additional 85 SUSs and 16 AXBTs were used.

The deployment vessel, HMNZS TUI (formerly USS AGOR DAVIS) steamed north of point A initially towing a low frequency source and then releasing charges set to detonate at 18.3 meters every kilometer (total 750 shots). BT drops were taken every 15 km (50 units expended) and 25 deep casts were conducted using sound velocimeter and salinity probes. Finally, a sediment core was taken at the mooring site.

The overall extent of the experiment is outlined to illustrate the reliability and performance required in this remote self-recording system. Clearly, the entire effort would be wasted if the array or instrumentation malfunctioned, or could be significantly impaired if the array was noisy due to strumming.

The second deployment of the MABS system was in a more coastal region. This deployment placed the array in the horizontal mode, at a depth of 438.9 meters in 1737.4 meters of water. This phase was principally a technology evaluation effort. Funding was not sufficient to instrument the array for a significant engineering study, however, some installation and environmental parameters were recorded. Basically, the installation technique and ease of deployment were validated.

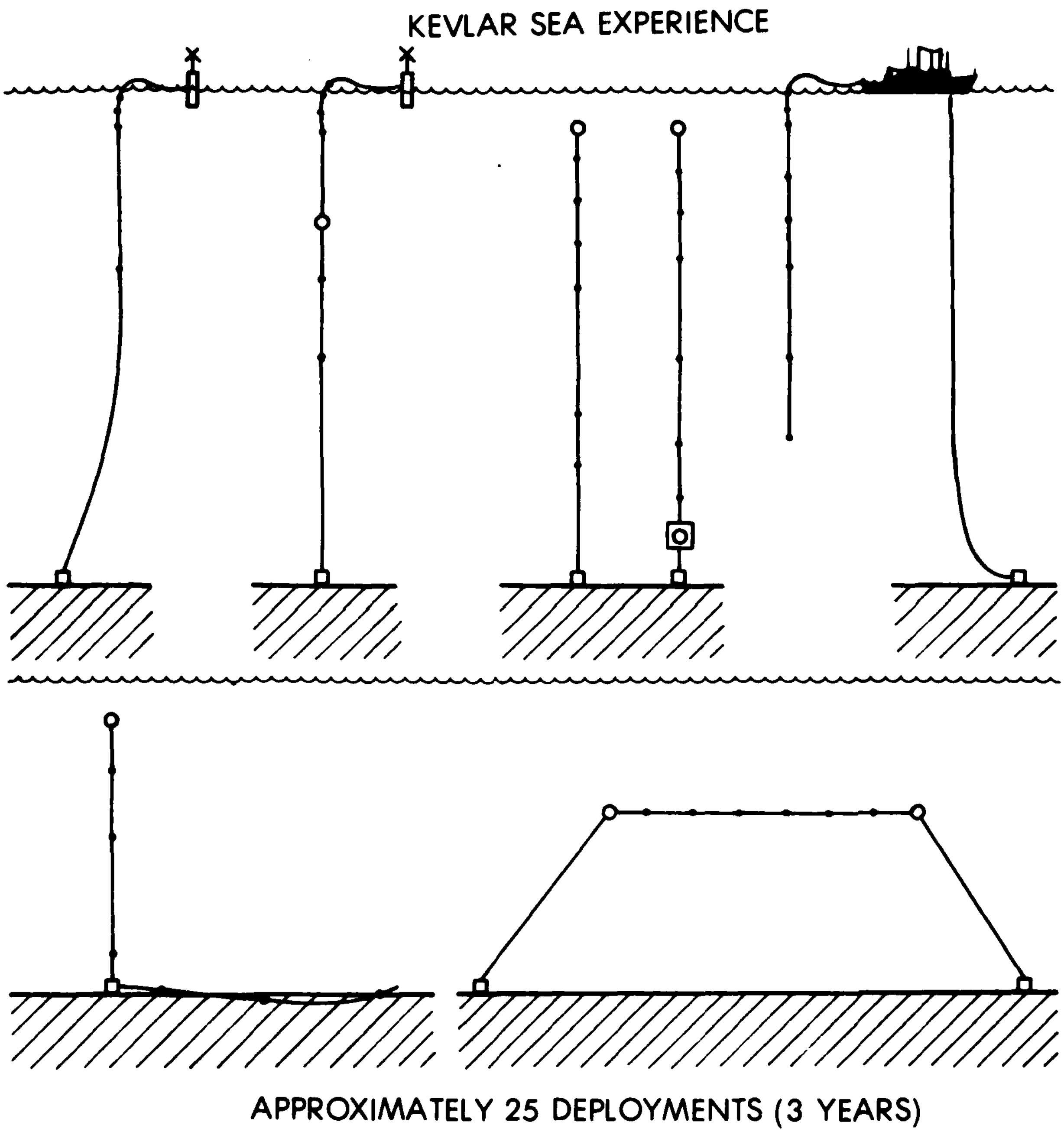
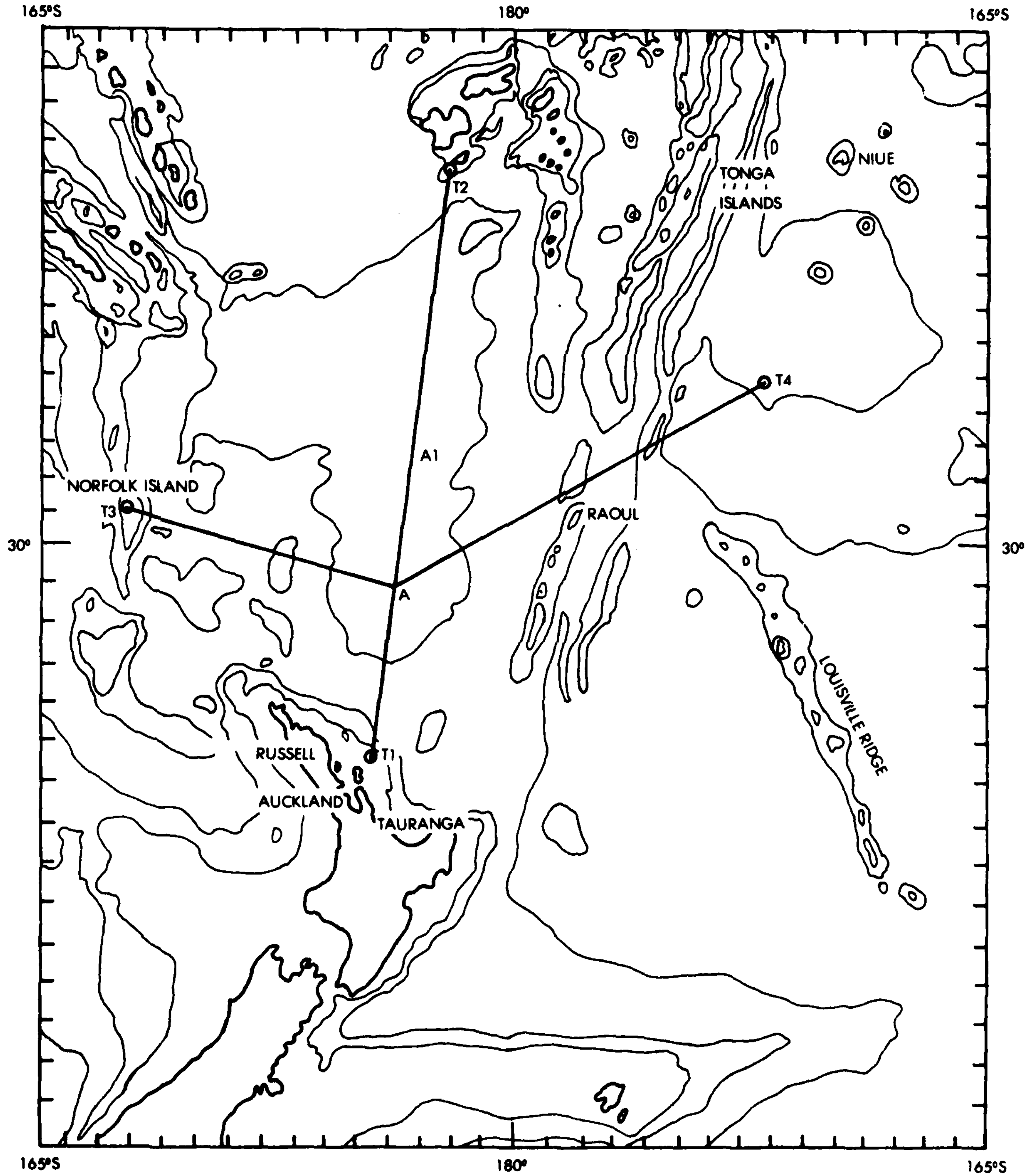


Figure 16 Various Kevlar Array Configurations



PROJECT SPAN THREE

Figure 17. Chart of Array Positioning

During both deployments, a full reel (five day continuous) of 14-channel acoustic data tape was produced. The only equipment malfunction was the internal malfunction of one hydrophone during the first deployment.

C. Hardware Description

1. Kevlar Array

The array consisted of four braided Kevlar ropes run in parallel and overbraided with a polyester jacket containing a fuzzy type fairing used to suppress strumming. Each rope contained nine no. AWG22 stranded copper conductors insulated with 20 mils of polypropylene copolymer. The nine conductors were helically wrapped around a TPR filler core to accommodate the Kevlar stretch. The conductors ran 1/4, 1/2, 3/4 and the total length of the cable, with TPR filler rope used the remaining distance in their respective ropes to form an electrically tapered array to reduce weight and cost. The resulting cable had an O.D. of approximately 1.9 cm, break strength of 88.96 kilonewtons, in-water weight of 124.7 kilograms per 1828.8 meters, permanent elongation of one percent at 50 percent of BS, and elastic elongation of three percent at break. The array was designed to facilitate the insertion of special in-line hydrophones and to possess no torque.

Philadelphia Resins Corporation fabricated the 1828.9 meter cable and cyclic-tension-tested a sample with an inline hydrophone in place a total of 40,000 cycles between zero and 22.24 kilonewtons without damage.

The array cable was shipped by air on a 1.8 meter diameter reel to New Zealand. There, the hydrophones were inserted into the cable by removing the outer jacket at the desired location; spreading the four ropes; inserting the phone mounted in its spreader cage; selecting the three required color-coded wires in the designated rope, drawing them out through the braid, and connecting them to the hydrophone utilizing slip-on connectors (Figure 18). The assembly was then whipped tightly and covered with a lace-up canvas boot. This process required about three hours per phone and was done as the cable transferred from the reel to the coiling crib. Six phones were used; the array had wiring capacity for 12.

The coiling crib was a 2.1 x 3.7 x .6 m truck box with a 190 liter barrel nailed in each end. The array and mooring lines were coiled around these barrels. Troughs were added to the sides of the box; hydrophones were placed in these troughs during the coiling to allow access to these units for subsequent calibration. The crib had the capacity to contain the array plus two lengths of 1828.8 meters each mooring lines (Figure 19). Once loaded, the crib was trucked to the ship, hoisted onboard, and lashed to the deck. During deployment, the array was coiled in and out of the crib by hand, thus avoiding the requirement for a large deck winch.

2. Mooring System

The mooring lines were 1828.8 meter lengths of Kevlar 29 Uniline fabricated by Wall Rope. The 1.1 cm O.D. parallel yarn ropes had a polypropylene jacket and fringe fairing; a break strength of 66.72 kn; weighed 1.36 kilograms per 304.8 meters in water; were torque free; and were precisely, permanently marked every 30.4 meters while under tension at the factory for exact length control, thus assuring precise buoy depth placement.

Parallel AMF acoustic releases buoyed up by four each 43.2 cm glass floats (90.7 kilograms of buoyancy) were used at the bottom of the moor. Due to the near weightlessness of the mooring line, upon release, the lower end would return to the surface allowing the array and mooring line to hang in a large loop. This approach is failsafe and allows for recoiling the array in the proper direction upon recovery.

All line and array end fittings and cable stoppers were Chinese finger type. These were produced by wrapping either Kevlar strand or flat braid around a thimble and lacing over the cable to be held in the fashion prescribed by Wall Rope (Figure 20). This simple and effective end fitting is inexpensive, easily applied in the field, will hold 100 percent of the break strength of the cable, and will allow it to pass unmolested through the thimble when required.

Mass weight cast steel anchors provided by New Zealand were used. A 907.2 kilograms unit was required for the vertical moor and two 1814.4 kilograms units equipped with cross rails to enhance horizontal holding power were required for the horizontal (Figure 21). Drag chutes were used when the anchors were free fall. The anchors were jettisoned during array recovery.

Because considerable tension might be encountered during array recovery due to ship drift (2000 - 9000 newtons), some type of puller was required on the stern of the recovery ship. This was easily accomplished by bolting on a special "V" type puller to an existing capstan. This increased the bending

Figure 18. Cable, Hydrophone, Spreader Cage and Canvas Boot

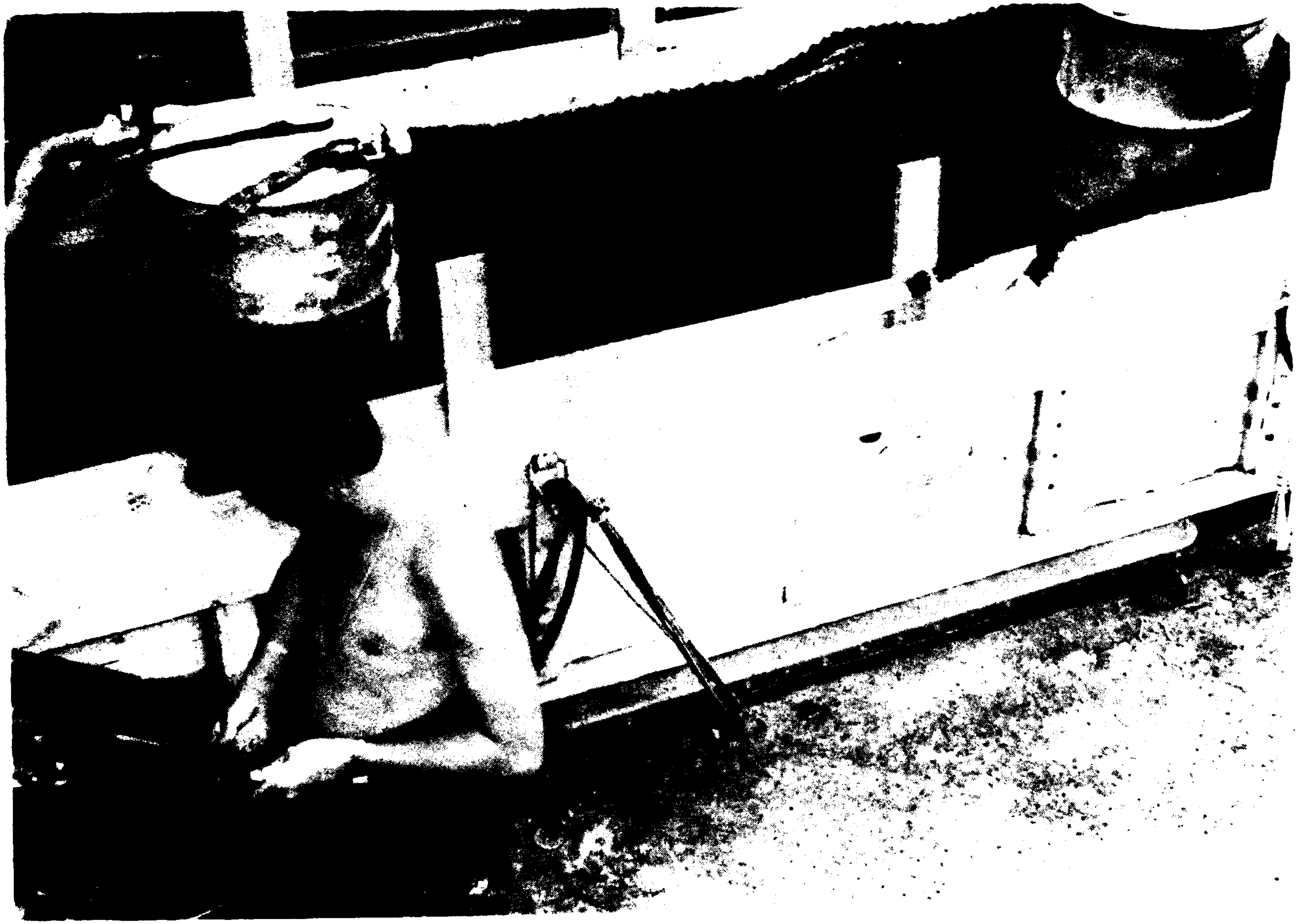


Figure 19. Array Cable Coiled in Crib

Figure 20. Application of Flat Kevlar Strands to Form End Fitting

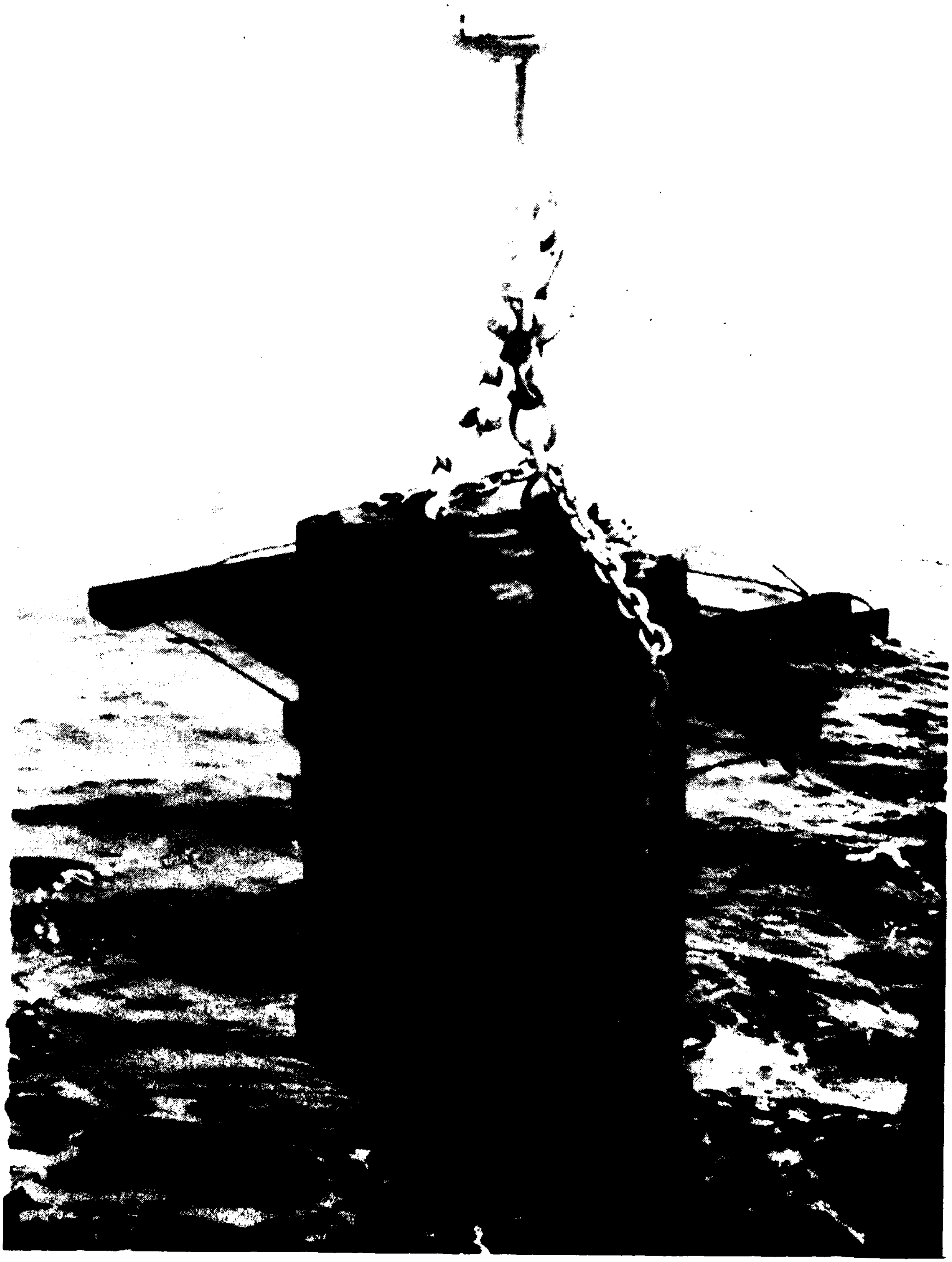


Figure 21. Cast Steel Anchors with Cross Rails Used in the Horizontal Mode

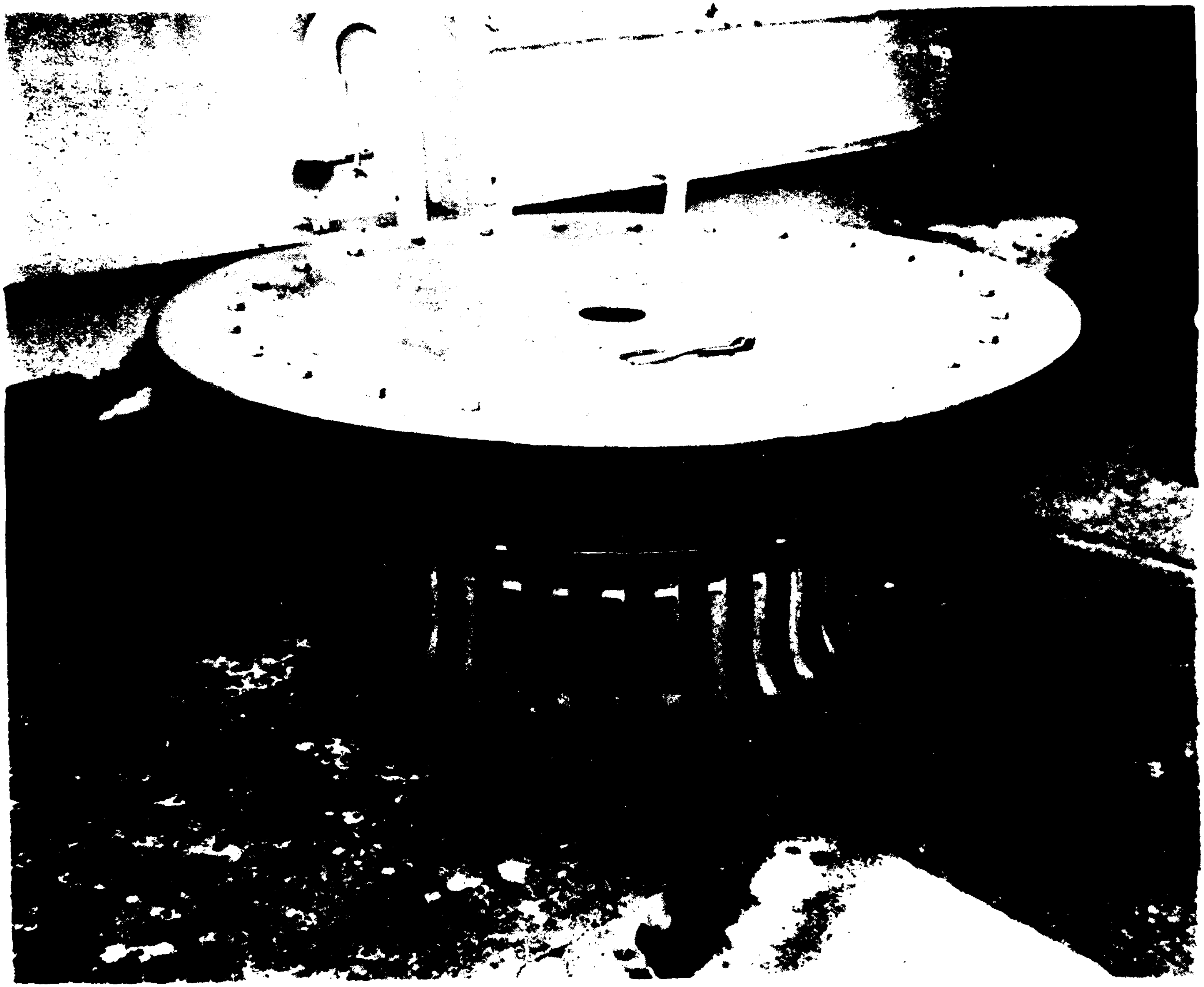


Figure 22. Neoprene "V" Groove Segments Fastened Between Plates and Fixed to a Capstan

diameter to approximately 1.3 m and required only 180° wrap around the wheel to develop the full breaking strength of the Kevlar line due to its wedging action (Figure 22).

D. Sea Operations

In both operations, the array, mooring system, and instrumentation were completely assembled, calibrated, tested and placed on deck ready for deployment in port prior to getting underway. This approach ensures maximum reliability, minimum effort at sea, thus, less weather dependence.

The deployment vessel (TUI), now on loan to the New Zealand Government, is a single screw ship with a large sail area, making it extremely unmaneuverable at slow deployment speeds, and furthermore, has limited deck space and at-sea lifting machinery. Therefore, the equipment and deployment plans were designed to accommodate these limitations. The only additions required to the ship's equipment was the $500 "V" puller previously mentioned and a satellite navigation system.

1. Vertical Deployment (Figure 23)

The first deployment was conducted on 18 March 1976, in sea-state 5, wind 20-30 knots, and sea and swell were 3.0 to 4.6 m high. The ship was brought up-weather several miles from the desired mooring point, and was allowed to broach starboard side into the weather. The 1814.4 kilogram MABS buoy was hoisted and released over the lee quarter as the ship drifted down-weather at approximately 1.5 knots. The array and mooring line were fed out of the coiling crib by hand on demand. The end of the line was preattached to the anchor which pulled the array off the deck into the water to complete the deployment.

This process required only 1½ hours, and was carried out in rough weather with an unfamiliar crew. An additional 35 minutes were required for the anchor to reach the sea floor; the descent rate was approximately 3.5 knots and was controlled by the size of the drag chute.

At completion of the experiment, TUI returned to the site 12 days later via satellite navigation, acoustically commanded the release on the buoyant lower end, and recovered the array in the reverse manner with the assistance of the "V" puller to inhaul the array. Because the hydrophones could not be bent around the puller, each phone had to be stoppered off with a Kevlar grip (Figure 24), the load relieved via a second deck capstan and a burden line until the phone was past the puller. (This process only required about three minutes, but revealed a problem for arrays which may contain many elements.) The recovery process required approximately 1½ hours, but was carried out only in sea-state 2.

2. Horizontal Deployment (Figure 25)

The horizontal deployment placed the 1828.8 m long array at a depth of 438.9 m in 1737.4 m of water. The simple deployment plan lowered the second anchor via a crown line to the bottom, thus hauling the array to depth as TUI drifted down-weather, and therefore was not required to maneuver. As the mooring load increased to about 680.4 kilogram horizontal force it was expected to halt the ship's drift, at which time the ship could apply power and leisurely spread the array and lower the anchor to the desired location. Redundant acoustic and radar ranging instrumentation was provided to ensure adequate real time position information of the array constantly during the installation (Figure 26). This was displayed on a vertical plotting board using scaled lengths of string to provide a visual representation of the system (Figure 27). In addition, a rigorous installation analysis had been carried out to predict the behavior of the array as a function of the controllable parameters, i.e., crown line length and ship's position. These computer-printed graphs were used in the deployment plan and referred to at sea during the installation.

Unfortunately, consistently bad weather delayed the deployment approximately two weeks and forced the deployment to occur during marginal weather conditions, which ultimately required TUI to maneuver into the sea, and resulted in "flying the anchor in" without adequate time to get good confirmation of the array depth. This illustrated the requirement for an installation vessel which can hold its heading while making little or no way in the water if exact array depth positioning or heading is required.

A bathymetric survey and chart was constructed prior to deployment. An excellent bottom was located which had a total depth variation of only 30 m over a 30 square kilometer area.

The installation began in state 4 seas by deploying the first mooring leg #1 anchor last. The mooring leg was 91.4 cm longer than the water depth and allowed the 544.3 kilogram, buoyant, syntactic foam corner buoy to remain on the surface for subsequent array attachment. Next, a radar transponder equipped navigation buoy was deployed, anchor last, three miles down-weather (northeast in the prevailing conditions). This marker was required as a real time navigational reference used to determine the ship's

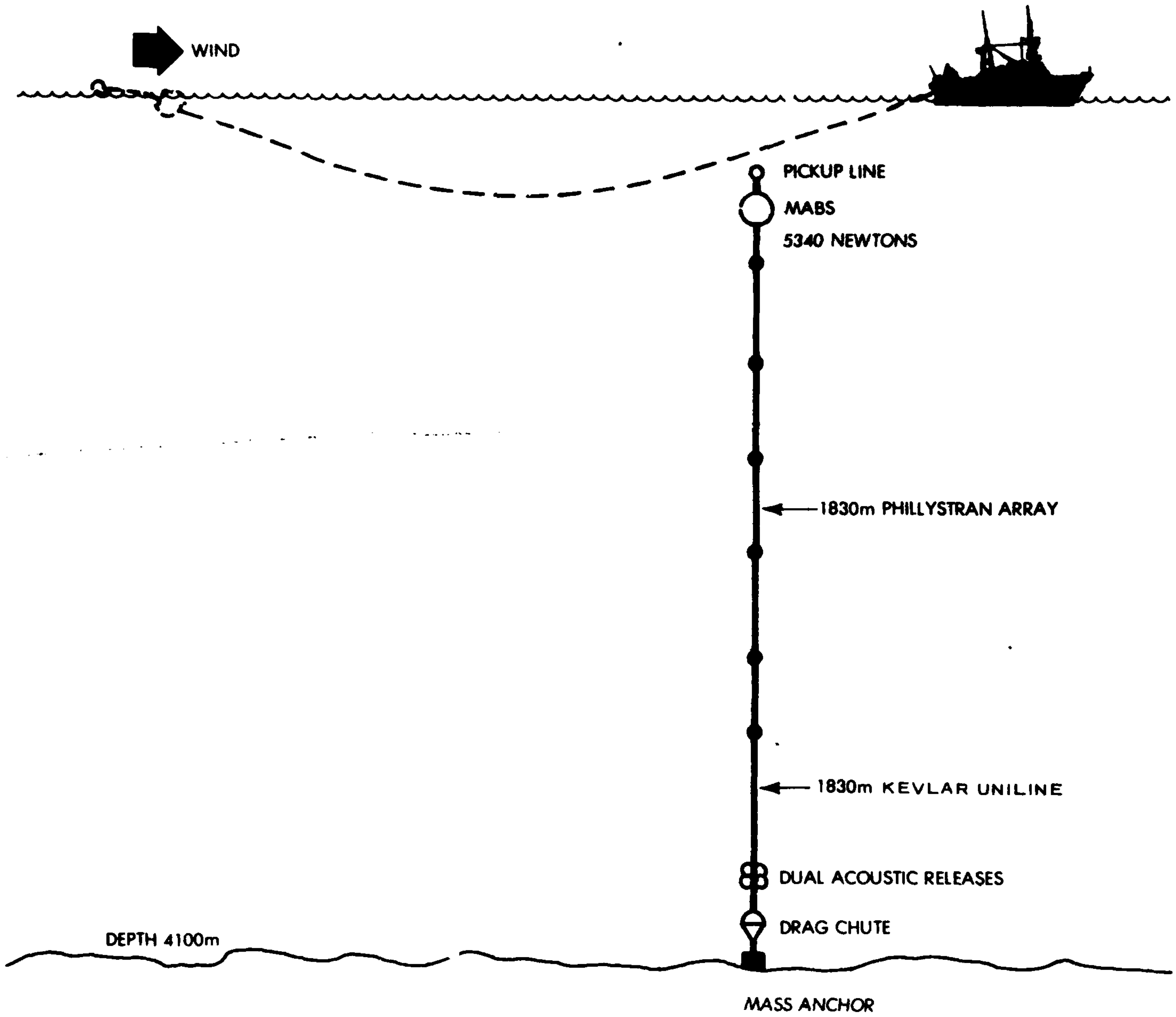


Figure 23. MABS Vertical Deployment

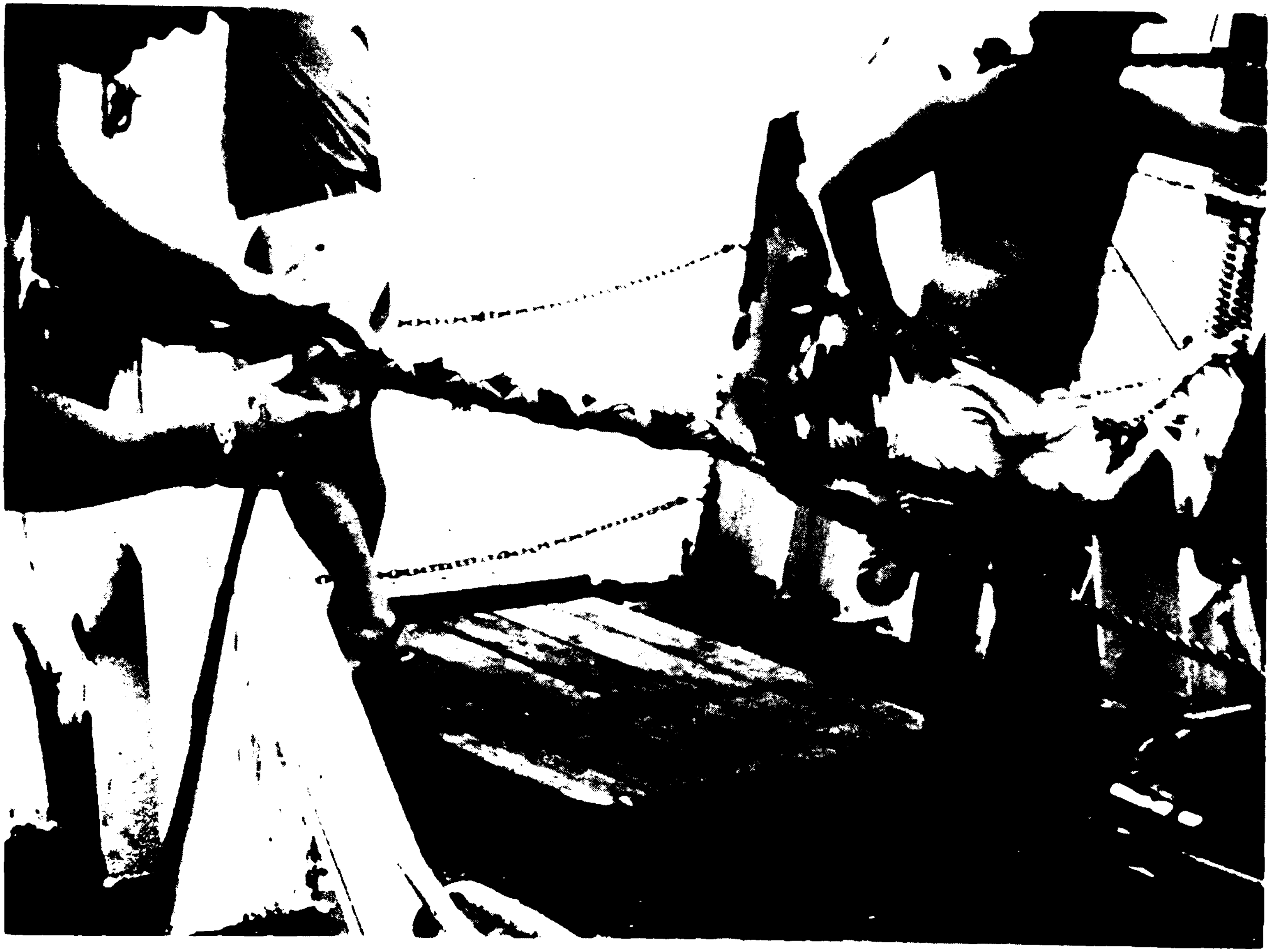


Figure 24. Stopper Being Applied to an Electromechanical Cable During Operations at Sea

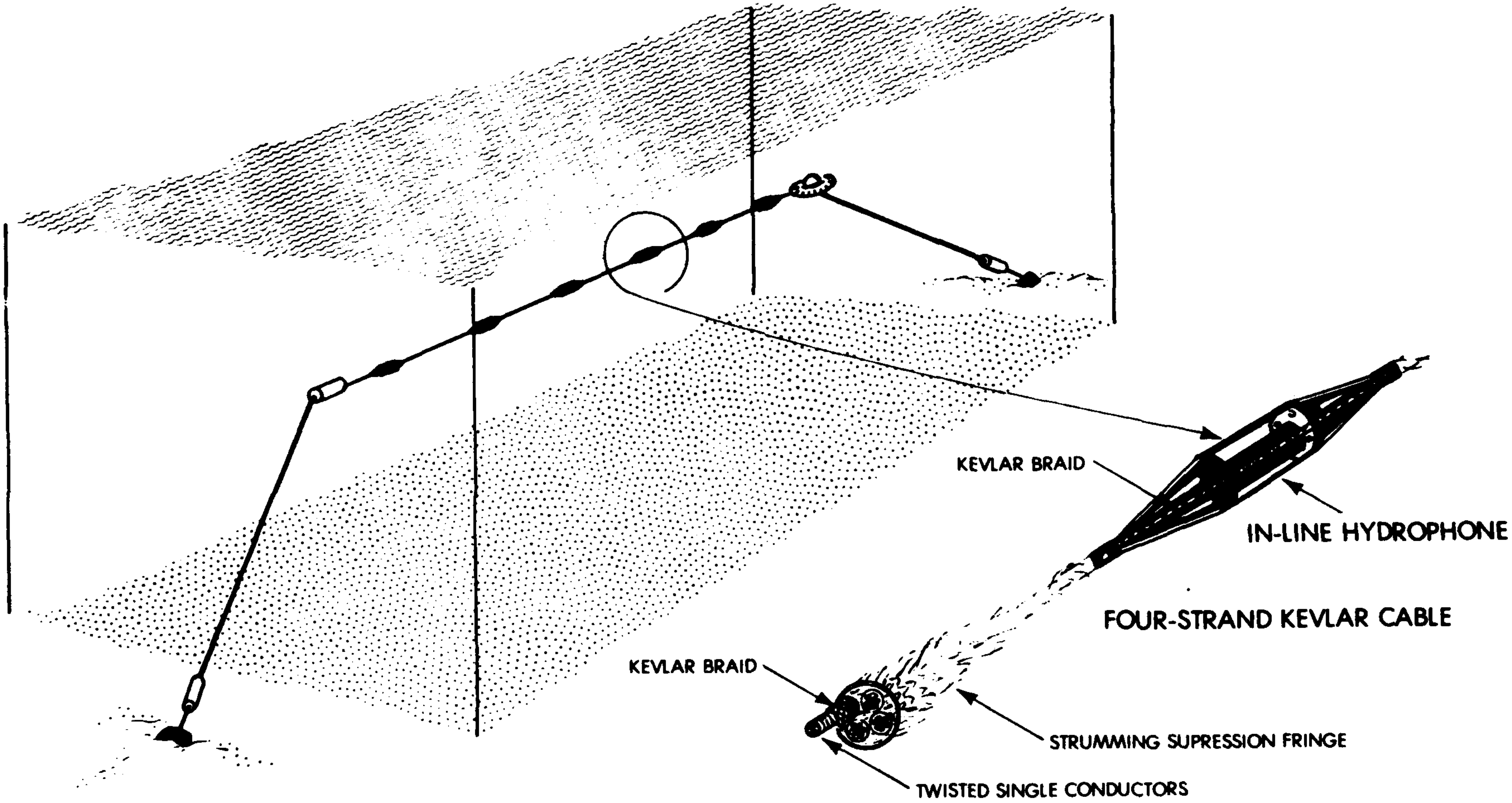


Figure 25. MABS Horizontal Deployment Illustrating a Coaxially Inserted Hydrophone

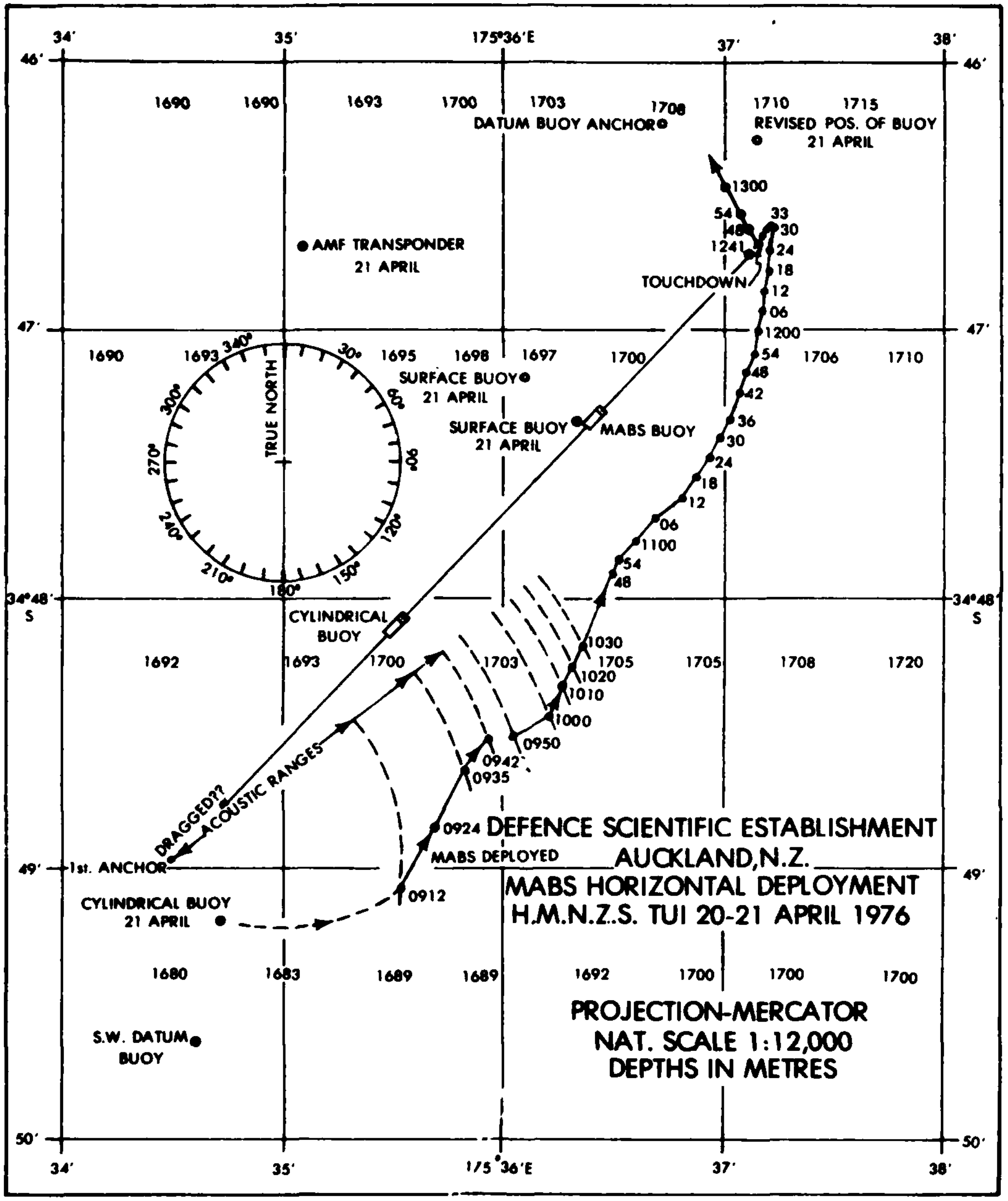


Figure 26. ‍Acoustic Positioning of Array

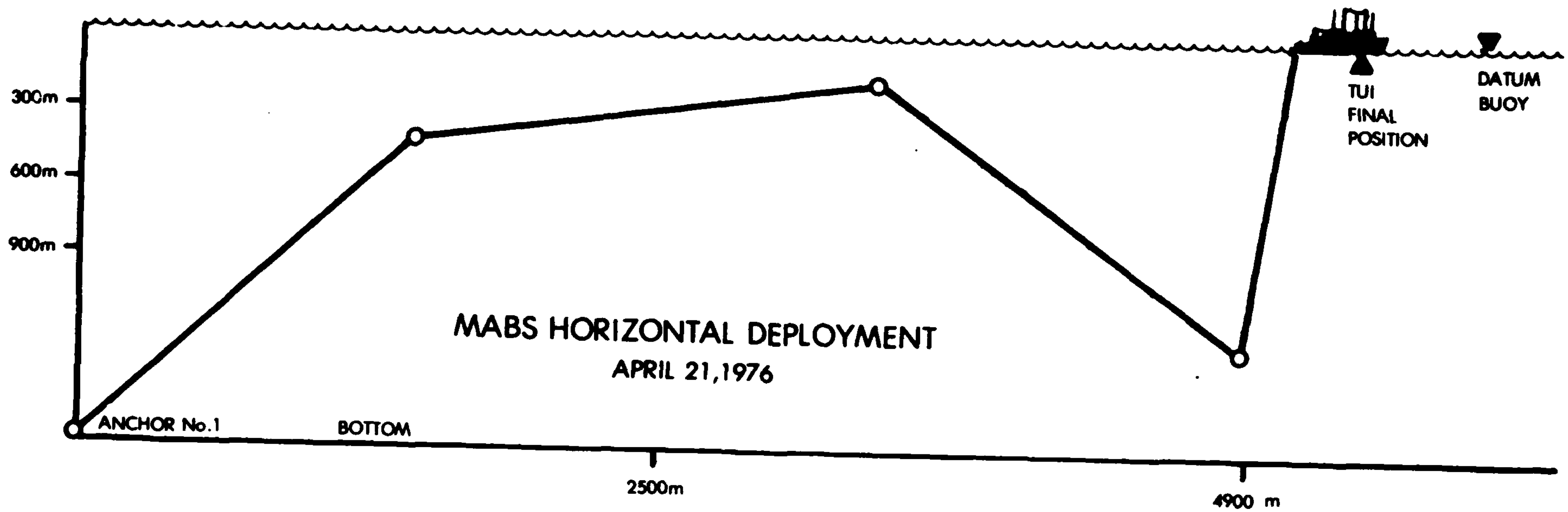


Figure 27. Visual Representation of Array Position

position relative to the first anchor. At the completion of this three-hour process, the weather had worsened to sea state 5; thus, the operation was discontinued until the following morning.

The deployment was resumed the following day in state 3 seas with 2.5-4 m swells. However, the ship's set was in the opposite direction, and required the ship to maneuver at slow speeds into the set. Fortunately, the Kevlar mooring line held the 1360.8 kilogram corner float through the rough seas the previous night; but, the self-recording depth sensor and current meter were shaken free of the moor and lost, thereby incurring loss of these measurements at that location.

The deployment continued by attaching the end of the array cable to the corner buoy and maneuvering up sea toward the navigational buoy #2 (Figure 28). The horizontal range of that buoy to anchor #1 was determined by acoustic ranging on an acoustic transponder release near the anchor, knowing the water depth and the radar range to the buoy. As the ship moved away from anchor #1, it would ultimately exceed the acoustic range; thus, the necessity for radar buoys (plus the redundancy).

The array was again deployed out of the coiling crib, the MABS buoy over boarded and released, and the second mooring leg deployed by hand from the coiling crib until the second anchor was reached. This anchor was then lowered away via a steel 1.27 cm diameter crown line using the ship's deep sea coring winch. The ship continued up sea at approximately 1 knot as the anchor was lowered away, which ultimately hauled the MABS buoy down. The depth of the second anchor was accurately obtained by using a free-running pinger attached nearby on the crown line. The direct and bottom reflected ping displayed on a fathometer gave an excellent record of the height off the bottom. The depth of the MABS buoy and the array was available on an intermittent basis by interrogation via an acoustic link, a depth sensor on the buoy.

These instruments, along with the pre-installation analysis, provided ample and redundant information for the moor setting. However, as the array neared the desired depth of 731 meters, the deployment was slowed down to a point where the ship lost steerage way and could not hold its heading into the sea. Therefore, the array was prematurely placed approximately 304.8 meters shallower than planned. This phase of the deployment required only 3½ hours, and clearly demonstrated the ease of deploying this large array which required only 159.07 kiogram, buoyant, synthetic foam floats attached along the length to render it neutrally buoyant.

Ship stern acceleration, plus crown line tension, were recorded during anchor #2 lowering. Unfortunately, the crown line tensiometer did not have the response required to record the dynamic fluctuation. Visual observation and recording, however, revealed large and unexpected dynamic loading on the crown line, which ranged between 907.2 and 3175.2 kilograms, and had the same six second period as the ship's heave near the end of the lowering. This anomaly (which could be disastrous in a complex mooring), along with a comparison of predicted insulation analysis, is being studied at NUSC, and results will be available in a forthcoming report.

The array was deployed for a five-day recording period; again, heavy weather persisted. A full reel of 14-channel acoustic data was produced, and no array malfunctions were indicated. In addition, records from a self-recording current meter and depth sensor attached near the MABS buoy were recovered. These records showed that the array remained at a nearly constant depth of 438.9 meters for approximately the total deployment period, except for a four hour interval when the array was driven down an additional 35.0 meters by a ½ knot current flowing normal to the array (Figure 29). This corresponds to a mooring tilt of approximately 13°.

The array was recovered in 18-20 knots of wind in a state 3/4 sea, and was brought to the surface by commanding the acoustic releases attached to the bottom of each mooring leg. Seven and one-half hours were required to recover the moor. No problems were encountered and all equipment was in a condition suitable for redeployment. The equipment was returned to port and repacked in a transportainer for shipment to the U.S. After arrival at NUSC, the array remained in storage for six months and was again successfully redeployed off Florida in the vertical mode.

E. Conclusions

The SPAN-3 experiment was a successful operation conducted on a small budget. A significant acoustic data base for the measurement program was produced and the reliability, economics, and versatility of the Kevlar technology clearly demonstrated. With the horizontal array mooring precedence, it is now feasible to proceed with plans for much more ambitious acoustic arrays with a reasonable degree of risk.

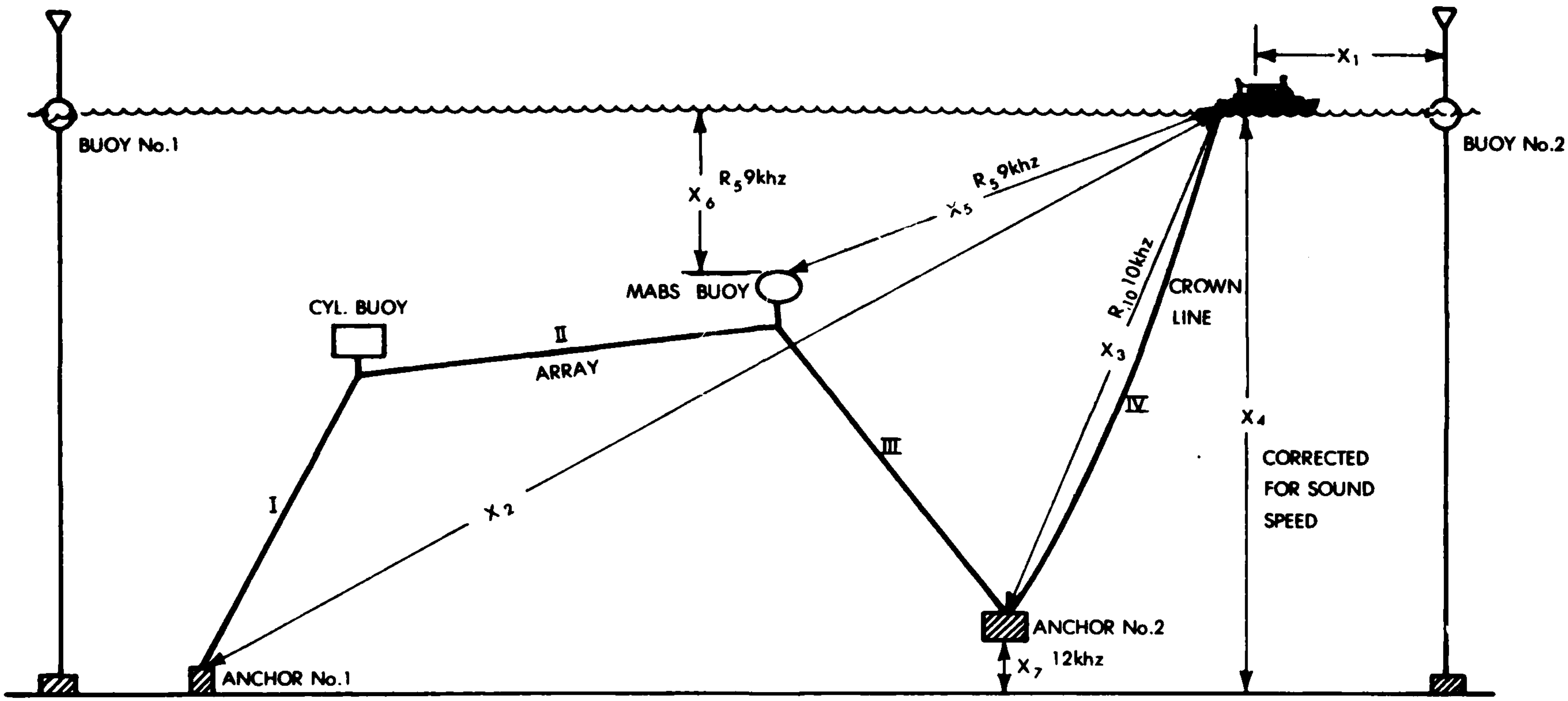


Figure 28. MABS Installation Parameters

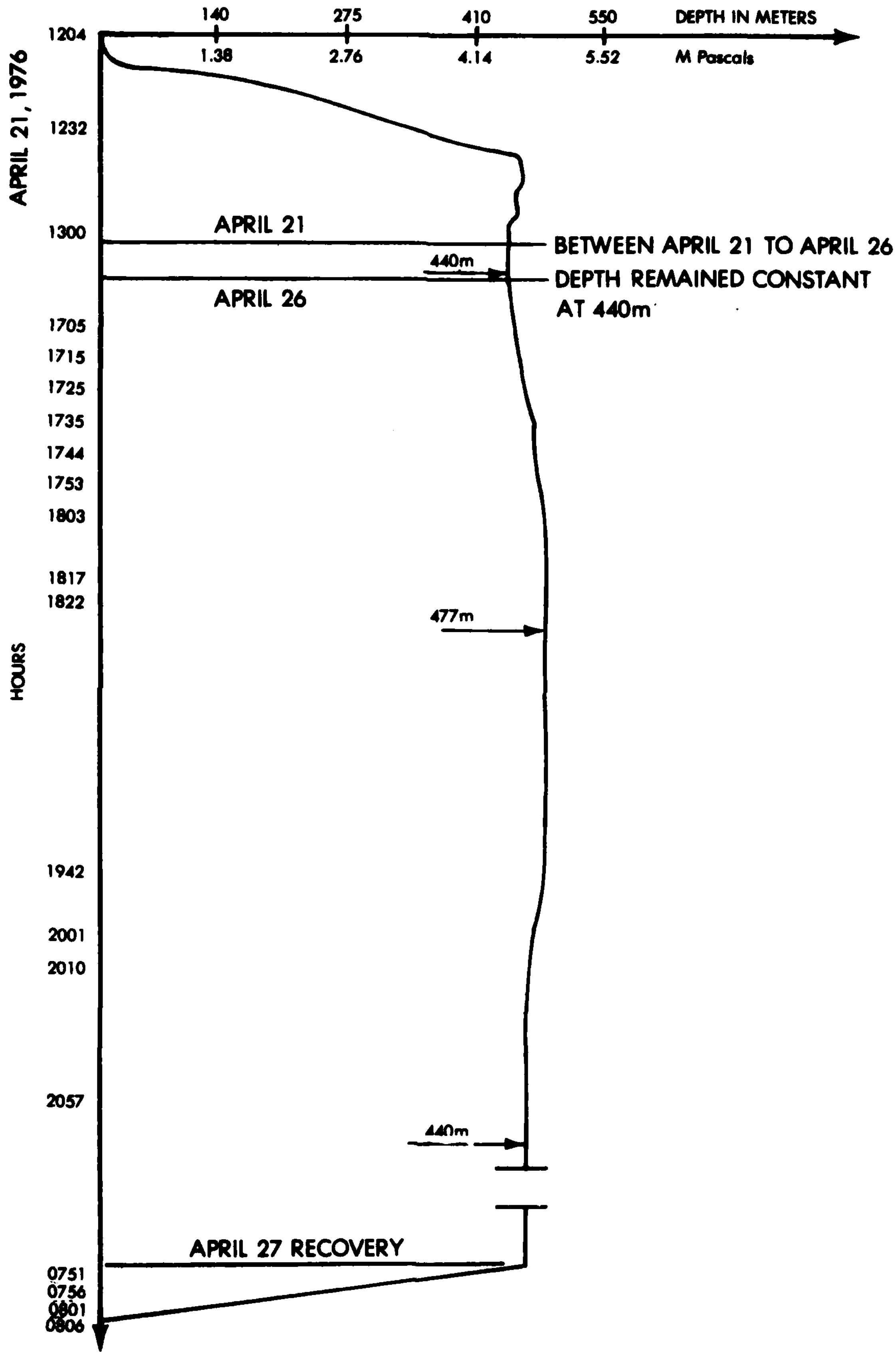


Figure 29. MABS Depth Record

VII. PREPACK, FREEFALL BUOY SYSTEMS

The free-fall, self-locking cable dispenser (Figure 30-A) is designed to pay out kink-free cable as it falls through the water. The self-locking device stops cable pay out upon impact with the ocean bottom. The collision drives a shaft into the center of the bail and causes the cable to form several loops around it, thereby locking the cable in place (Figure 30-B). Each bail is composed of a pre-twisted mechanical or electromechanical synthetic fiber cable. The cable is pre-twisted during winding to prevent a helix from forming as the cable is pulled from the bail in deployment. As the cable is wound to form the bail, it is coated with a matrix material such as depolymerized rubber (DPR). This ensures a constant payout resistance force and avoids any advance payout that would cause snarling.

Basic system design can be tailored to fit any requirement from small, hand-deployed models to large, long-term sensor buoys. Some obvious applications include low watch circle marker buoys for navigation and position relocation; such various military applications as moored sonobuoys, and environmental buoys; and man overboard or lost object marker buoys. If the cable used must have a synthetic fiber strength member for weight reduction, then enough elongation with good fatigue life to accommodate surface waves must also be provided. In shallow water, polyester is a good choice; but in deep water, Kevlar appears to be the better choice. The high strength, excellent fatigue resistance, and small elongation under load provide the necessary properties for long tension members. Long lengths of synthetic fiber electromechanical cable are also possible if some prior consideration is given to the design of the electrical conductors. This is thoroughly discussed in Chapter III.

Several buoys of this type were constructed as navigational aids. This particular design consisted of a canister, mass weight, cable seizing hook, shear pin, and cable bale (Figure 31). The cable bale was contained in a canister equipped with a smooth rub-ring to facilitate cable payout. In this design, various size bales can be used, or several bales can be placed in series. The weight was faired to enhance free-fall stability and to maximize the terminal velocity. A shaft extended one bale length ahead of the mass weight and was restrained in that position by a shear pin. Upon bottom impact, the pin was sheared and the seizing hook end of the shaft was thrust up into the bale allowing the cable to take sufficient turns onto it to stop the cable payout. This was all contained in a cylindrical-shaped canister with a hemispherical nose. Deployment was facilitated by the design, permitting it to be rolled over the side of a ship and allowing free-fall stability.

Two bales were constructed by Philadelphia Resins Corporation with the following specifications:

1. Wound with PS29-B105

Length of bale:	31.1 cm
O.D.:	20.96 cm
Diameter of core:	10.2 cm
Length of yarn wound:	approx. 3505.2 meters
Strength of yarn:	1760 newtons
Weight of bale:	8.3 kilograms

2. Wound with PS29-S-59 (8 part braid)

Length of bale:	31.1 cm
O.D.:	19.3 cm
Diameter of core:	10.2 cm
Length of yarn wound:	approx. 3352.8 meters
Strength of braid:	1840 newtons
Weight of bale:	7.34 kilograms

Both were wound with "Z" or counterclockwise twists; both were contained in a matrix of DPR 242. For item (2), however, slightly less yarn was wound and less matrix material was used, thus, the lighter overall weight. The measured pull-out load was 3.3 to 4.4 newtons for item (1) and 2.2 to 3.3 newtons for item (2).

These devices were successfully deployed as navigational aids with the experimental acoustic array positioned off New Zealand (this array deployment is described in Chapter VI). The canisters were thrown off the ship at the desired location after the attached polyform float was placed in the water. Ship navigation was obtained relative to the surface floats by radar positioning.

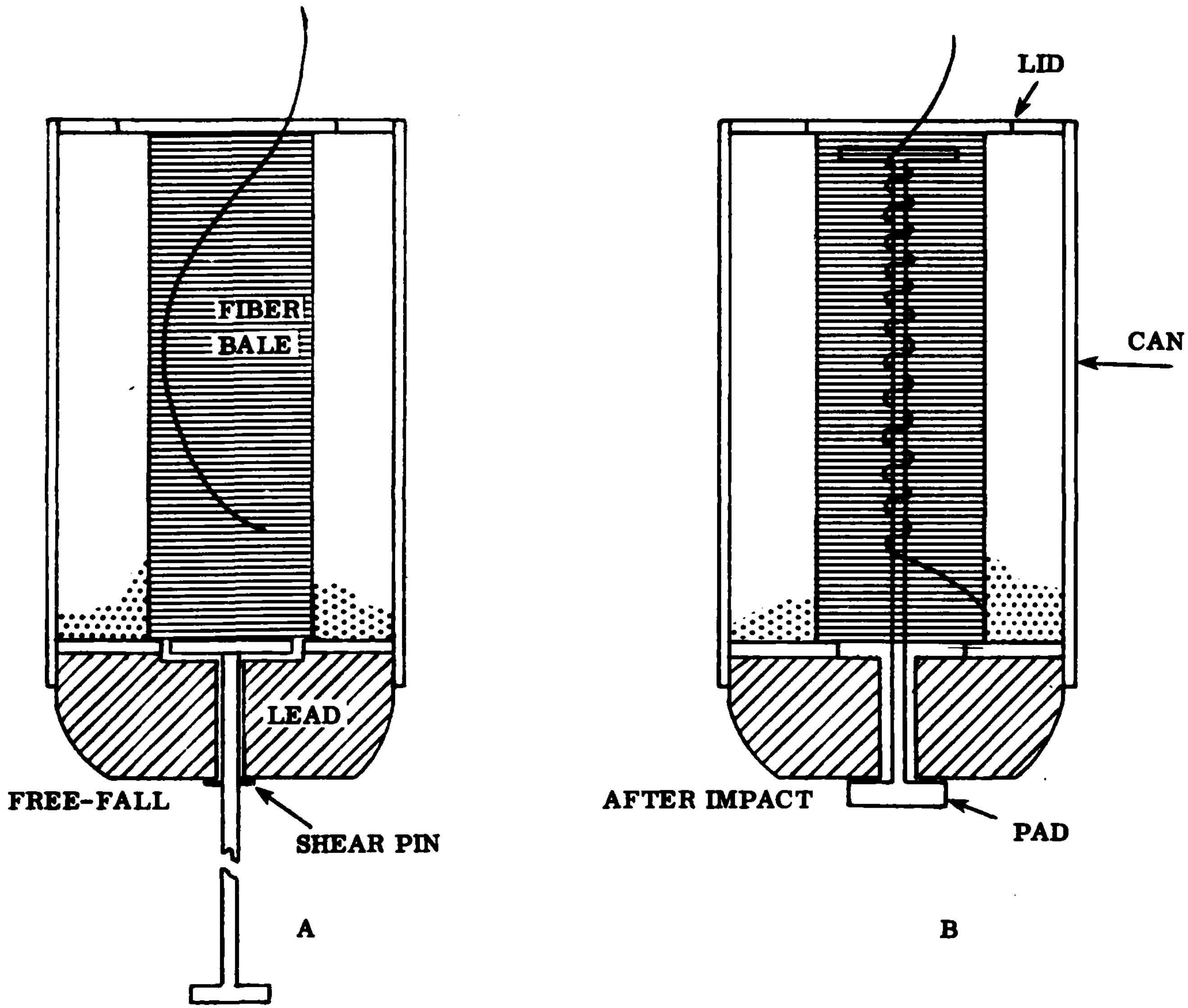


Figure 30. Free-Fall, Self-Locking Cable Dispenser for Ocean Buoy Systems

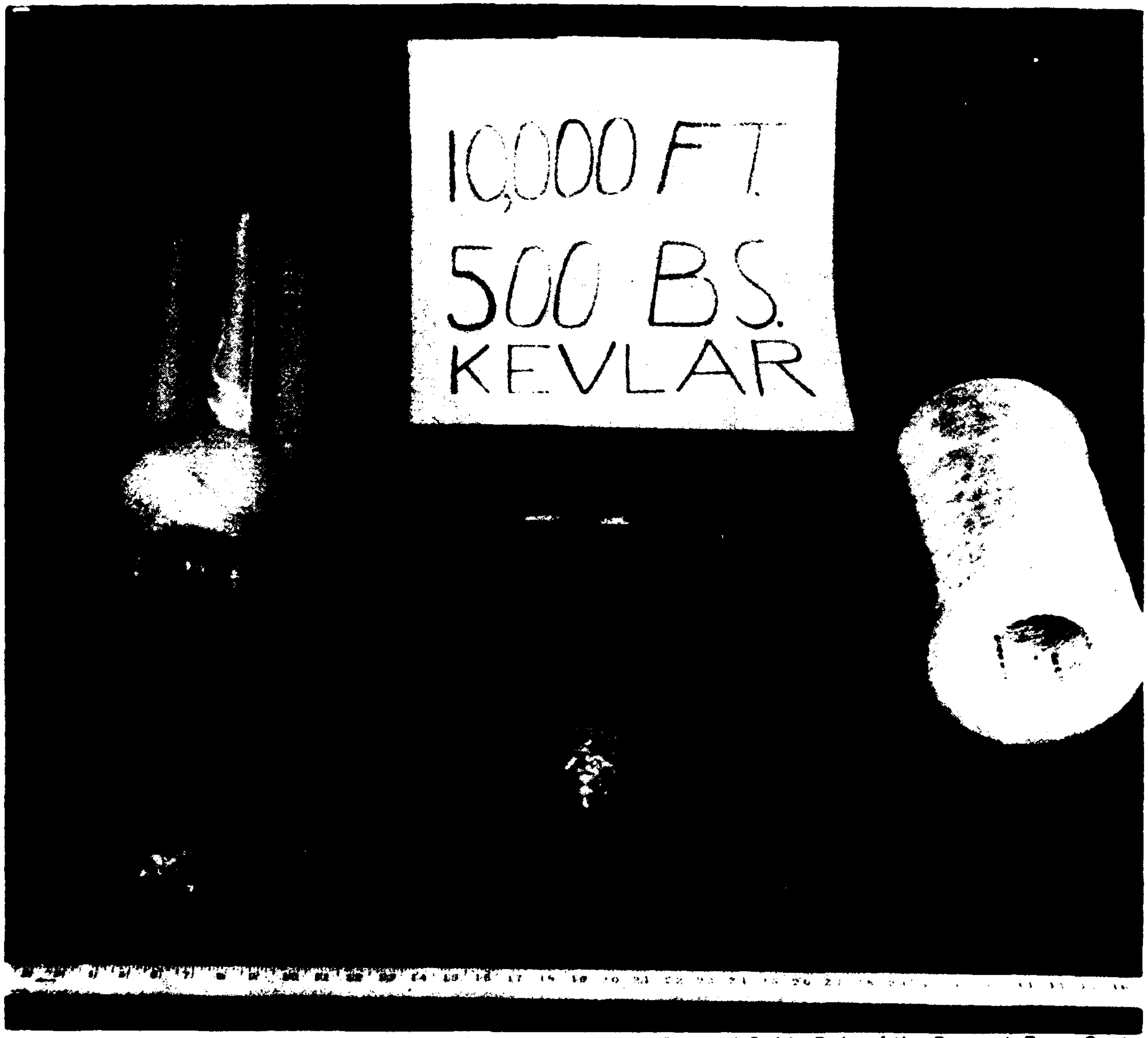


Figure 31. Canister, Weight, Cable Hook, Shear Pin and Cable Bale of the Prepack Buoy System

VIII. LONG-TERM TENSION FATIGUE

Tests conducted at various laboratories have shown that specimens of aramid fiber stressed under relatively high loads (> 70%) failed suddenly after varying time periods. Data points taken by the Naval Air Development Center (Brett and Holler, 1975), show that at loads above 70 percent of break strength, failures occurred at midspan within a time range of a few seconds to several days. Only samples without overstressed points, loaded below 70 percent, have been suspended for long periods without failure. Information published by DuPont and data from a report on the stress rupture behavior of Kevlar 49 aramid fiber indicates that Kevlar, on the average, is not as unstable above 70 percent as might first appear, but that considerable scatter does exist in time-to-failure at high load (Chiao, Wells, Moore and Hamstad, 1973). In addition, any non-uniformities in rope construction can lead to localized overloading and early failure at high loads. The conclusion can be drawn that the higher the applied load, the shorter the fiber life at high loads.

In order to determine a realistic rated breaking strength and a safe long-term working load on ropes, two contracts were awarded for the study of long-term tension fatigue. One contract was awarded to Wall Rope Works to investigate the tension fatigue of parallel fiber ropes; the second was with Philadelphia Resins for braids. Because these tests (begun in FY77) are long term by nature, this chapter can only review the experimental approach, since the results are not available as of this writing. The work to date has been published in a Naval Ocean Research and Development Activity Technical Note (Ferer, 1977).

A. Parallel Fiber Rope

The parallel construction rope was chosen for testing because:

1). Fiber crossover is minimized, therefore, fiber self-abrasion in tension-tension cycling is minimized.
2). The line is torque free which may be essential for deployment considerations.
3). Highest strength conversion efficiency of all the rope constructions is produced.
4). Terminations have been proven both simple and successful.
5). The Navy has this line in stock and is presently using this line; thus, the planned data is needed to establish long-term safe mooring loads.

Wall Rope began the parallel aramid fiber tests in late FY77. In addition, several polyester Uniline ropes were included for comparison purposes. At present, eight Kevlar Uniline ropes and two polyester Uniline ropes, all with a nominal diameter of 1/4 inch, have been tested. (See Table 10 and Figure 32.)

Table 10. Time to Failure versus Dead Weight Load.

Uniline Rope	Percent of B.S.	Time to Failure
Kevlar	95	1 min.
Kevlar	90	1.5 min.
Kevlar	85	6 min.
Polyester	85	50 hrs.
Polyester	75	continuing

The plans are to tension three additional Kevlar Uniline ropes at 70 percent, 60 percent, 25 percent, and a fourth at whatever load is needed for more information.

B. Braided Rope

The braided construction rope was also chosen for testing because:

1). The effects of strand damage or local imperfections in the rope are averaged over a short length of the cable.
2). The rope has excellent flexibility, a small bending radii, and is easy to fabricate.
3). Electrical cores are utilized.

Philadelphia Resins Corporation is continuing a program for tensioning urethane impregnated strands. The wet tension fatigue program has been completed and is discussed in this report (Chapter XI). The dry tension portion of the test has been an ongoing effort for over three years; results to date show no indication of ill effects at 20-30 percent of break strength (BS = 266 N).

Six cable samples will be installed in a frame and subjected to 40, 50, 60, 70, 80, and 90 percent of the break strength. Cable elongation will be measured hourly for the first eight hours, daily for the first five days, and weekly for a period up to one year. If and when a cable fails, a new specimen will be installed. This replacement process will continue until a maximum of three cable failures have been achieved for each load condition or until the one-year time period has elapsed. This information can then be plotted on a log time to failure versus percent of break strength as with the parallel fiber rope.

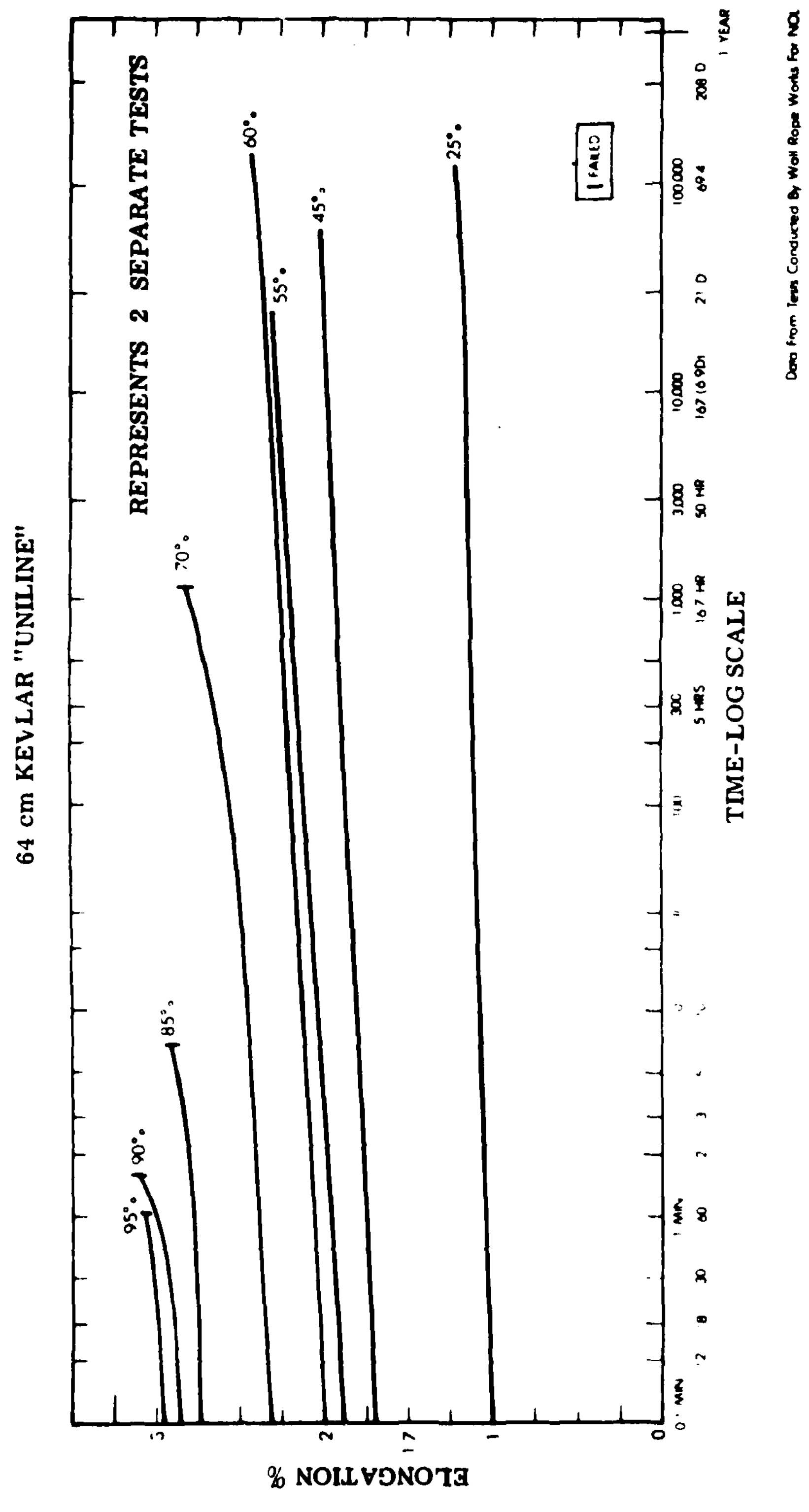


Figure 32. Lifetime and Creep vs. Deadweight Load

IX. HIGH STRENGTH ROPE

Conventional synthetic rope constructions have been used successfully for a wide variety of mooring assignments over the last twenty to thirty years. In the larger sizes, however, conventional constructions become inefficient. Radially directed forces present in braided or twisted construction rope are proportional to the square of the diameter, and can crush inner fibers. Internal abrasion, also intensified by the radial forces, further limits load capacity.

The high strength, high modulus, Kevlar fiber is sensitive to abrasion and radial compression. Transverse loads for ropes of equal diameter are higher for the Kevlar fiber and accentuate the problems. That the parallel yarn rope approach appears to be capable of resolving these problems becomes apparent at this point. Transverse forces are eliminated except when the rope is bent over a radii, and in any terminations. With the parallel yarn method, efficiency should remain constant with size. In addition, cycle loads (tension-tension) will not cause internal abrasion. Finally, any elongation will be limited to material creep which is very small, rather than to constructional elongation which is an order of magnitude higher.

The two major problems in developing a large sized parallel fiber rope are:

a). Maintaining uniform fiber length throughout the cross section.

b). Projecting current termination methods to the larger sizes.

Plans are underway to develop a 1334 kilonewton break strength rope; and, if successful, a 5338 kilonewton break strength rope will be developed.

Wall Rope began the tests late in FY76 (see Table 11). Six lengths of 1.59 cm Kevlar parallel fiber rope (each covered with a thin jacket) were arranged in parallel around a polyester fiber core to form the first model high strength line. The break strength of the individual ropes was 240 kilonewtons, an efficient use of the fibers that composed the rope. However, when the ropes were assembled into the large line and all spliced together at the ends to form the eyes, the sample broke at 979 kilonewtons — not the expected 1441 kilonewtons (6 x 240). This was obviously a problem in load sharing. In the next attempt, the ropes were individually tensioned and individually spliced at the termination, but this sample broke at 845 kilonewtons; again, this was a load sharing problem. The small amount of aramid fiber elongation and the lack of a yield point under tension caused the shorter fiber or rope to take up the tension first. After failing, allowing another to tension, etc., it causes a cascading effect which allows the entire assemblage to break at a fraction of the design strength. A long sample is an absolute necessity for testing a Kevlar rope of this size; each spliced eye end fitting must be almost 23 meters long.

In order to model the large line, the same rope design was again constructed, using polyester. The stretch allowed the shorter test specimens to show any blatant flaws in the design. The polyester specimens (Table 11) were successful and plans are to proceed with a six-inch diameter, multicore polyester rope.

Table 11. Results of Multicore Uniline* Tests

Description of Individual Ropes Used			Description of Multicore Rope		
Construction	Expected BS (kn)	Actual BS (kn)	No. of Ropes Used	Expected BS (kn)	Actual BS (kn)
Kevlar** 48 yarns 36,000 Denier Polyester Cover	256	240	6 Ropes Dummy Center Core Polyester Jacket	1441	979 2 = 845
Polyester 28 yarns 35,000 Denier Polyester Cover	32	32	7 Ropes Polyester Jacket	226	1 = 49,442.4 2 = 234

*Trademark of Wall Rope Works
**Trademark of DuPont Corporation
BS = Break Strength
All breaks were in the free rope.

X. CABLE END FITTINGS AND ACCESSORIES

This section describes the extent of the work completed on Kevlar rope and cable end fittings, grips, and stoppers. In general, Kevlar ropes and cables can be terminated by using either steel cable or fiber rope-type end fittings. However, since Kevlar is a fiber, the rope-type terminations usually produce higher breaking strength. The type of termination to be used is highly dependent on the cable construction, numbers of electrical conductors, and size limitations on the hardware.

Work previously reported on parallel fiber ropes indicates that this construction permits a large variety of termination techniques, with the eye splice as an excellent choice. This eye splice was developed by Wall Rope Works for their Uniline parallel fiber rope, and will develop 100 percent of the break strength of either mechanical or electromechanical parallel fiber rope. Served or double helical wrap construction has been principally limited to the use of epoxy-potted or wedged conical sockets. The end fittings required for braid construction were also considered. This series of tests concluded that a properly applied eye splice is again a good choice from a variety of possible methods.

A good approach for mid-line grips or stoppers appears to be splices utilizing a Chinese finger-type grip. The development was centered on producing a grip that is relatively simple, quick and dependable.

A. End Fittings

All the termination tests, with six noted exceptions, were conducted on a Phillystran* PS-29-S-41J cable, which is a 0.58 cm diameter Kevlar-29 braided cable with a maximum break strength of 23130 newtons. Tensile tests proved this break strength to be the ultimate strength of the six-foot specimens; the break strength for longer specimens may be slightly higher. The cable is constructed with four layers of aramid fiber braid over 0.25 cm nylon core and covered with a 0.0064 cm polyurethane jacket. This particular rope was chosen because it is representative of the construction of both mechanical and electromechanical rope. The various methods of termination were chosen because they have been used successfully on other types of rope or cable. Experimentation began with quick and simple knots, then progressed step-by-step to the complicated, but more efficient, eye splices.

1. Rapid Rope Terminations — Sharp bends, necessary to form a knot, weaken the fibers on the outside of the bend. These fibers are the first to strain and break, throwing the load to other fibers, which continue the cascading effect. Because of the aramid fiber's reduced transverse properties and low elongation, knots in this material will be even less efficient. However, for comparison purposes, both bowlines and clove hitches were tied around a 4.45 cm steel bar and tested. These two knots were chosen because tests on other fiber ropes indicate that, of the various knots possible, bowlines and clove hitches were the most efficient. The bowlines tied in the aramid fiber rope began to slip at about 9341 newtons, which is only 40 percent of the rope's break strength. The clove hitches broke at 13789 newtons, or roughly 60 percent of the break strength. Removal of the polyurethane jacket made no difference in the results.

For any rope or cable, a series of turns over a capstan or drum, with the bitter end fastened, is the quickest and easiest method of termination. This next series of tests involved taking three wraps of the aramid-braided rope around a 12.7 cm diameter capstan. Slippage was prevented by inserting the bitter end into a hole in the capstan and knotting it. The ratio of the drum diameter to the rope diameter (D/d) was 5.0:0.23 or 21:1. The minimum recommended ratio is 20:1; the preferred ratio is 50:1.

Five samples were pulled to destruction. Most breaks were mid-cable breaks with a few parting at the tangent point. The average ultimate strength of the specimens was 18680 newtons. This method is roughly 80 percent efficient - a poor strength conversion percentage attributed to the short sample length and the inability of individual strands to readjust within this length.

2. Wire Rope Terminations — Wire rope terminations included in this study were pressed sleeve fittings and cable clips. Use of this hardware is a quick, convenient method of forming an eye around a thimble in the conventional steel cable manner.

In the first set of samples, the eye at each unjacketed end was fixed with 0.635 cm wire rope cable clips. The rope was bent around a heavy duty galvanized thimble previously polished to remove any burrs. Three clips were installed on each end, 2.54 cm apart, and tightened. The cable was then tensioned to 4450 newtons and the clips were retightened. In testing, the lines all parted near the clips and averaged 21796 newtons break strength, representing an efficiency of about 92 percent.

*Trademark of Philadelphia Resins Corp.

The second series of tests in this category began with the need to determine the minimum number of pressure fittings required and whether it was necessary to remove the rope's jacket before terminating. Figure 33 shows a jacketed specimen with one hydraulically swaged fitting at each end. The specimen failed near the thimble at a small percentage of break strength. A decision was made to remove the jacketing material from the rope and to use a minimum of four swaged fittings. The fittings were slipped onto the rope to form an eye, a polished thimble inserted, the eye pulled tight, and the fittings compressed. Each specimen broke near the pressed sleeves at an average break strength of 21660 newtons. This strength conversion of 94% is only slightly better than the cable clips.

The two preceding techniques seem to be drastic methods to utilize for fibers, but results indicated here and results reported by others for both static and dynamic testing have been satisfactory. These methods have produced 85 - 100 percent efficiency, however, there is some evidence that stress concentrations limit long-term loading to less than 65 percent of ultimate strength (Riewald, 1975).

3. **Socket Terminations** — The objective of this series of tests was to compare efficiency and installation time involved in socketing to other methods of termination. Epoxy potting tests utilized the recommended Phillystran resin, hardener, potting head, and procedures (Philadelphia Resins Corp., 1976). Nevertheless, the specimens realized only 92 percent of the ultimate break strength. Again, this lowered break strength probably results from the short specimen length. The cable breaks were all at the epoxy head (Figure 34), indicating that certain strands carried more of the load.

A number of tests were conducted using a Preformed Line Products "Dyna Grip" fixture. The termination was made without the rods normally used when end fitting steel cable (Figure 35); a metal bushing was inserted in their place. Numerous attempts were made to break the cable, but all tests ended with the braid slipping out of the fitting at about 5340 newtons. By adding additional layers of braid at the termination and bending them over both sides of the tapered insert, the point of slippage was increased to 8900 newtons. Additional attempts to improve this fitting proved futile.

Two newly designed sockets were also tested; one looks promising. Both sockets are shown in Figure 36. The conical-shaped fixture allowed the braid to be inserted up through the center, bent back over the cone, and bound securely by whipping. In this end fitting, the maximum stress load was at the bend and the rope failed at a low percentage of ultimate strength. The fitting on the upper half of Figure 36 consists of a solid rod with a few grooves. The braid is slipped up over the rod and tightly whipped. This fixture needs more testing, but shows promise at this point.

B. Splices

This section covers the variety of splices attempted in developing a simple, quick, dependable method of strength transfer. Variations included the length of braid, numbers of crossings, crossover spacing, inclusion of a "lump" to which the splice can be secured, and the use of cement to fix the strands. The splice is easily adaptable to various conductor strength-member arrangements and permits leading out conductors at any point. In effect, it doubles the number of strength members at the joint, and slowly tapers the stressed area, eliminating sudden changes in the load transfer points. The splice can be completed in the lab or in the field by any reasonably competent person and with a minimum of hardware.

Eye splices have, in addition to the attributes previously mentioned, a comparatively low mass. The relatively light, tapered area avoids a sudden transfer from a low moment of inertia to a higher moment of inertia, e.g., potted sockets. Eye splices, including the thimble, are inexpensive and involve little weight increase. However, in order to avoid collapse of the steel thimble used in forming the eye, thimbles much stronger than normally used for equivalent diameter synthetic fiber rope sizes must be employed. In addition, the thimble should be carefully checked to avoid any burrs or other cutting surfaces.

Beginning with the PS-29-S-41J cable, several variations in splicing techniques were attempted. In the first series, specimens of this rope were tightly bound 45.7 cm from the end, and all four concentric layers of braid unbraided to this point. The numerous strands were then separated into four equal parts, flattened out, and covered with contact cement. Next, the bundles were wrapped in opposite directions over the thimble and around the cable at carefully marked intervals. The assembly was then served and coated with neoprene. The average break strength of several samples was 21350 newtons, which was 92 percent efficient. However, all breaks were at the thimble in the unbraided portion of the rope. This is the area of uneven tensions and strand crossings.

Successive attempts involved expanding the outer braid back to the 45.7 cm mark and exiting the center braids from an opening at that point. This procedure was continued with the three remaining concentric layers until all four braids branched from the same location. The order in which the braids were back-spliced were varied, but this method produced poor results. The efficiency was in the region of 60 percent.

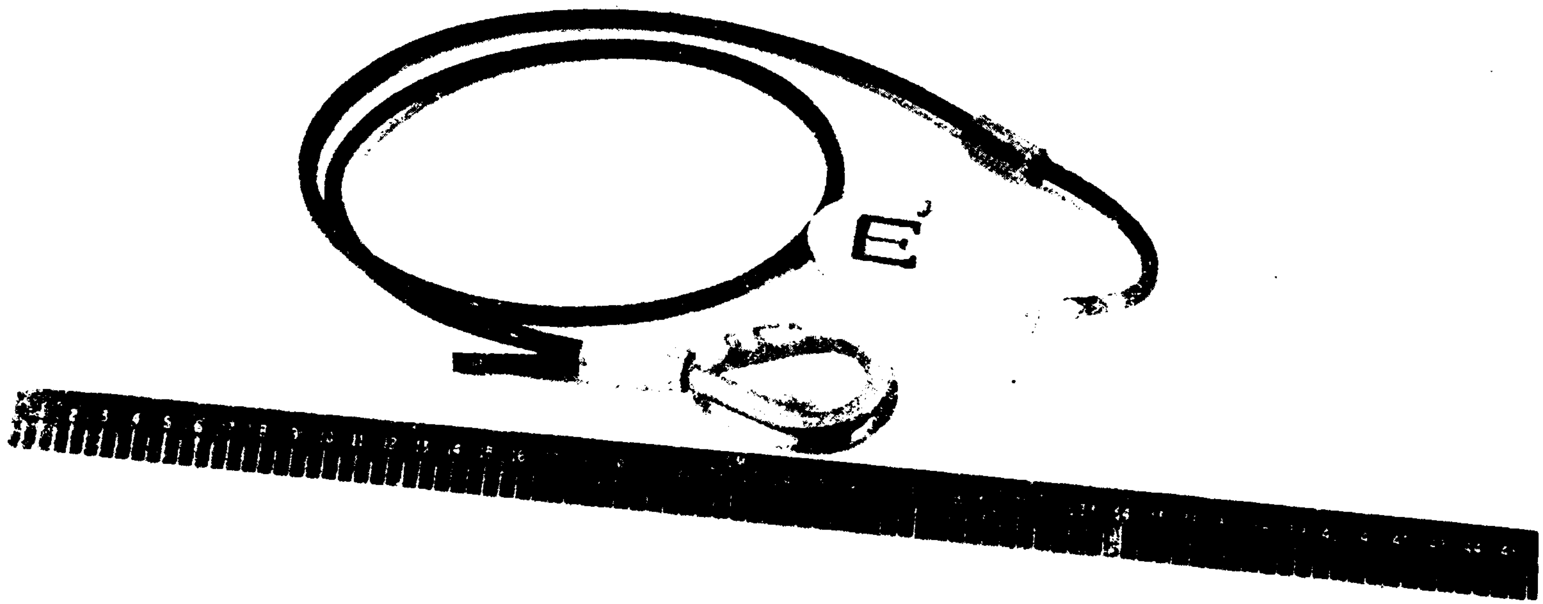


Figure 33. Phillystran Braided Cable with a Micropress End Fitting Pulled to Destruction

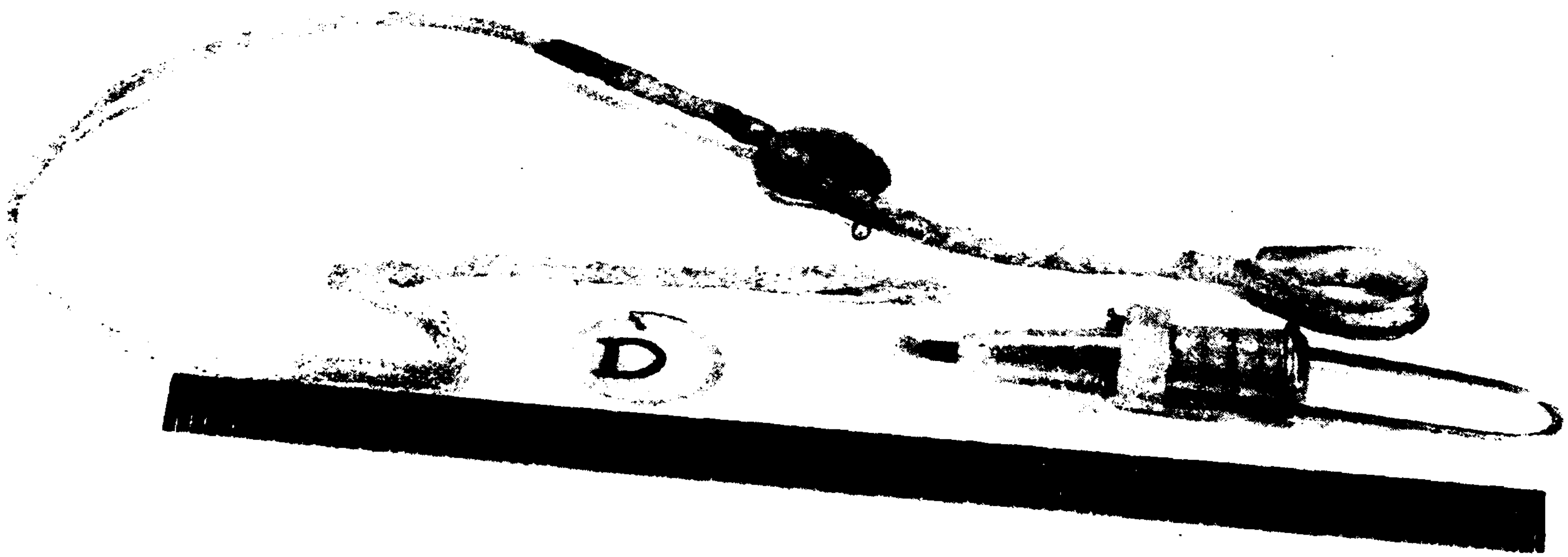


Figure 34. Phillystran Braided Rope with an Eye Splice which Survived the Epoxy Potted Termination

Figure 35. Phillystran Braided Rope and Preformed Dyna-Grips Pulled to Destruction

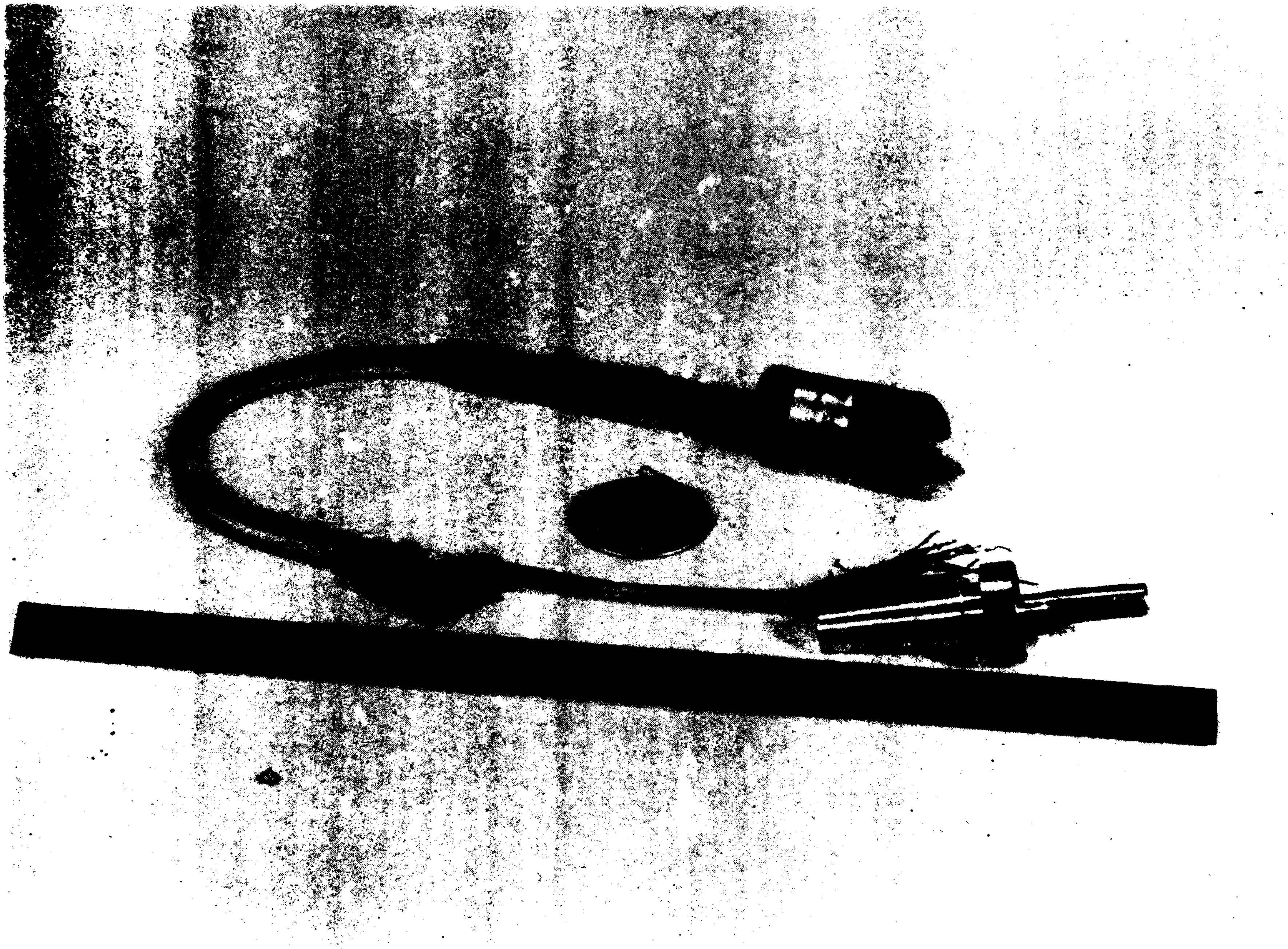


Figure 36. Phillystran Braided Rope in Which the Braid Over Rod Survived the Braid Through and Over a Cone End Fitting.

Next, the Wall Rope method (Wall Rope Works, 1975) of back splicing an eye was used, but with modifications. Approximatley 1 meter of 1.9 cm diameter, parallel construction, Uniline aramid rope was separated into four equal bundles. The four strands were wrapped on the braided aramid test rope, over the thimble, and back around the braided rope. A section of hollow braid was slipped over the parallel fibers at the thimble for protection purposes. Most specimens tested broke a strand near the eye, but broke at the ultimate strength of the braided cable. This indicated a need for slightly stronger strands for splicing. Moreover, no slippage occurred prior to breaking at nearly 100 percent efficiency. Figure 37 depicts one of the specimens.

At this point, a decision was made to try the modified Wall Rope splicing technique on specimens of lines being used at sea. The first was a 0.6 cm polyester Nolaro* line that had been terminated at both ends by this particular splice and deployed at sea. Upon completion of a three-week subsurface buoy moor usage, the line was returned to the lab, the ends cut, and an additional Wall eye splice added to complete the sample. The specimens were tested and breakage occurred in the center at 9340 newtons, the original break strength of the cable. Figure 38 displays the new and used splice and the midline break.

Finally, a section of 1.9 cm Uniline electromechanical cable to be utilized during a major at-sea experiment was end fitted. The cable had a 64 kilonewtons break strength. Termination was by two different methods neither of which used any of the original cable for the strength transfer. The entire cable was run through a section of pipe welded into a thimble (Figure 39). One end of the cable was bound to the thimble by four groups of 91.4 cm long parallel strands, the other end by flattened braid. The braid slipped slightly and tended to bunch the cable cover, nevertheless, both ends held. The cable parted in the midsection at 100 percent of the break strength.

A cyclic impact fatigue test was conducted at Preformed Line Products (Cyclic Impact, 1975) on a parallel constructed, Kevlar 29, Uniline rope to evaluate the material and its termination for ocean applications. A 4.4 m, 62.3 kilonewton breaking strength sample with Wall Rope spliced end fittings was installed in the impact testing equipment and loaded with 11 kilonewtons. The arm of the machine was raised until the sample went slack and then released at a repetition rate of 18 cycles/min. The impact produced a 2g load in the line, or 22.25 kilonewtons, and several oscillations per impact cycle. The sample survived a total of 100,000 cycles before the test terminated. The sample was then broken and found to have a residual breaking strength of 54.25 kilonewtons, or a 12.9 percent reduction in strength due to the impact loading. This test illustrates the exceedingly high fatigue life of this mooring line and end fitting.

The conclusion is that the termination of both parallel strength member and braided strength member cables, mechanical or electromechanical, is easily accomplished by an adaptation of the end-fitting techniques used for Uniline ropes. The process is achieved simply by obtaining several feet of parallel strand, forming four equal bundles, braiding up the cable to the end and over the thimble, and back braiding over the cable. The length of the braid and number of crossings and spacings have been carefully worked out to maximize the strength. Coating the strands with contact cement or Neoprene during splicing gives the fiber body and increased friction. A raised "lump"bound to the cable over which the strand ends can be served to prevent slippage is an important feature of this splice. Finally, the resulting splice is served with yarn and coated with Neoprene for protection. The completed termination resembles the Seaman's Stopper Splice.

Two samples of Kevlar 29 Uniline were terminated by the Wall Rope eye splice, and deployed by WHOI in shallow-water surface buoy moorings. The first sample was inadvertently cut free after 26 months, the second recovered after 29 months. Both lines were initially statically loaded at 12.5 percent of ultimate strength, however, the dynamic loads imposed by storms were much larger. Although the mooring lines show a strength reduction after 29 months, the fiber and its termination performed extremely well. A number of core yarn samples were removed from the rope and tested. Eighteen breaks averaged 5515 newtons tensile strength, while similar samples from new rope averaged 5860 newtons.

C. Stoppers

To take up a load on a cable at some point other than the bitter end occasionally becomes necessary. An excellent method is the mid-line eye splice or "stopper." For example, this type grip has been used with the earlier defined MABS array to attach an anchor at any desired array location without interrupting the cable (Swenson, 1975). The grip can be used to support instrumentation along a suspended cable or remove loads for mid-line cable repairs. Figure 24 illustrates a stopper being applied to an electromechanical cable to install in-line instrumentation. An accepted approach in constructing the eye is to wrap a large bundle of parallel strands or flattened braid around a thimble. The strands hanging from the thimble are divided into four groups

*Trademark of Columbian Rope Co.

Figure 37. Phillystran Braided Rope with Eye Splices, Each Made with Four Lengths of Parallel Aramid Fiber

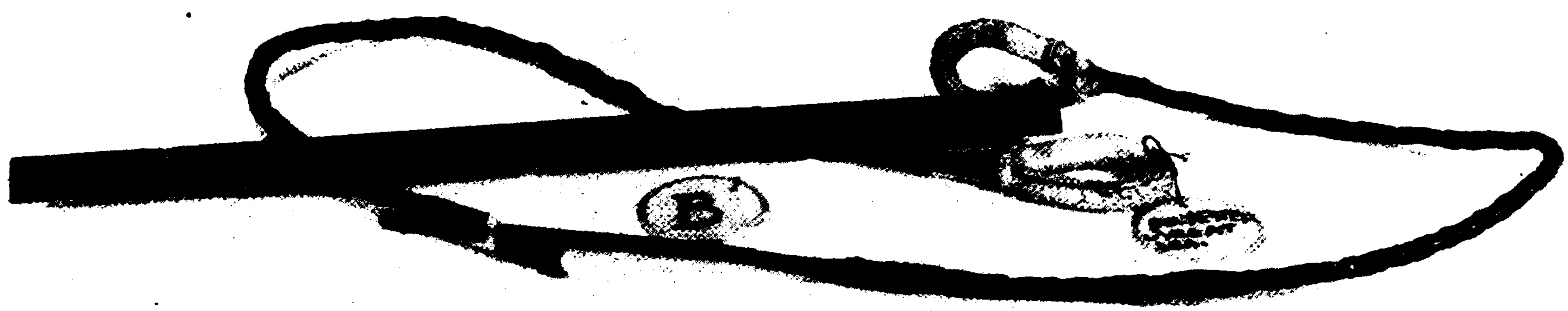


Figure 38. Nolaro 1/4 Inch Polyester with Eye Splice Termination. Rope Failed in Center of Test Section

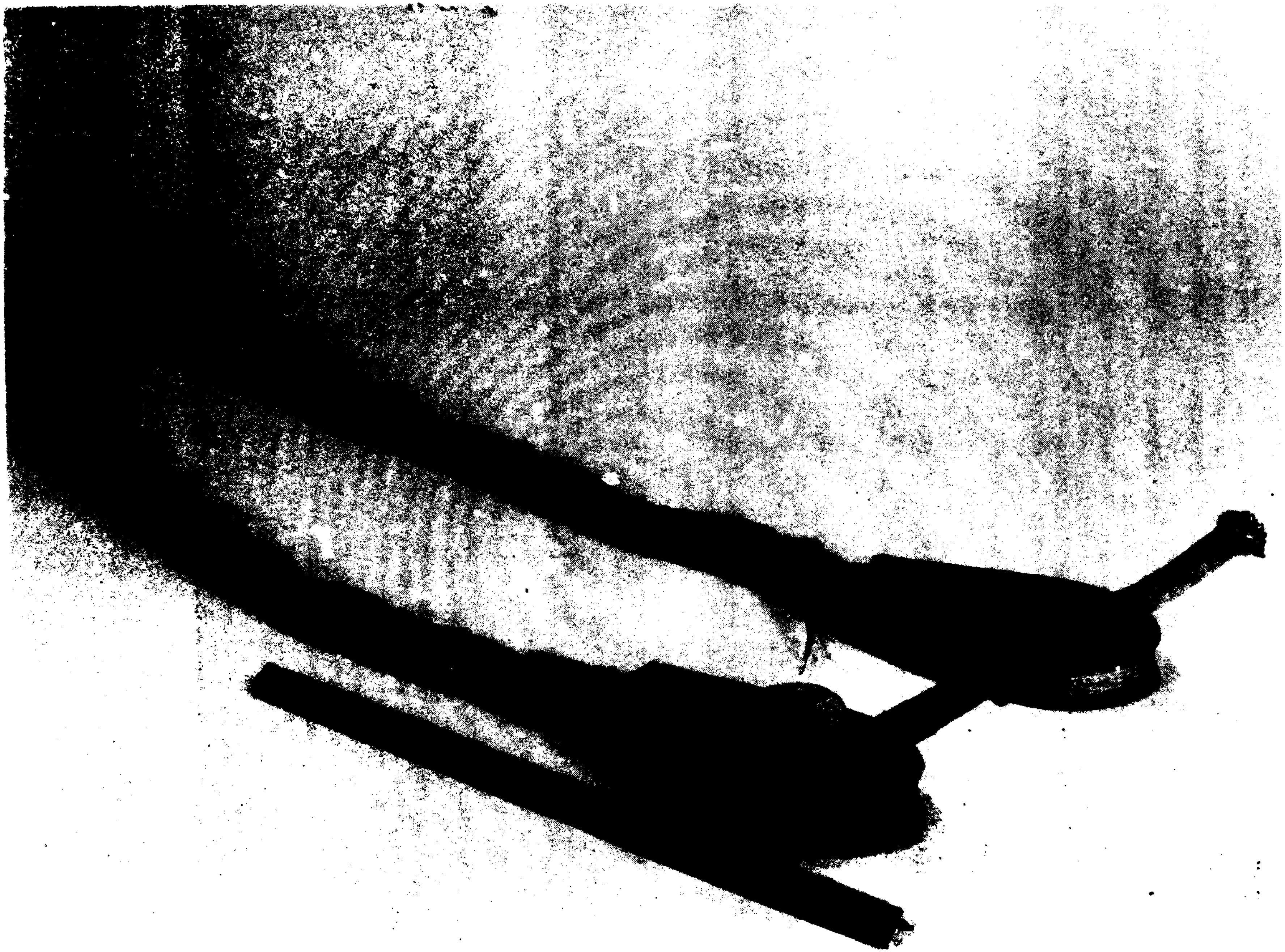


Figure 39. Parallel Fiber 3/4 Inch Aramid Cable with Eye Splices. Cable Failed in Center of Test Section

and braided along the cable in the same fashion as the normal eye splice. This grip can then be used as an end fitting or as a stopper. Grip strength can be made much greater than that of the line to be held, and can be applied in a few minutes, with little instruction required. As the tests show, however, methods of application are important to develop full strength.

Several variations of eye splices that have been used successfully as end fittings were applied to mid-cable sections. The application techniques were altered to minimize the installation time involved, although reduced time usually resulted in reduced strength. Almost all held to 30 percent of the rope's break strength, however, to develop the full 100 percent required several careful steps. Again, as with the terminating splices, the tightly bound section of line or "lump" against which the splice ends can pull without slipping, proved to be very important. In addition, the use of contact cement will greatly reduce the chance of slippage.

Figure 40 is a photograph of two spliced cables with three separate splices. The two eye terminations on either end are constructed of the previously described Seaman's stopper-type splice. The mid-line splice is fabricated in the same manner; however, it connects the end of one rope to the mid-section of the other. Of all the samples tested, the ultimate strength of each center splice was the ultimate strength of the flattened braid used to make the splice.

D. "V" Pullers

Properly constructed aramid fiber rope or cable is light, torque free, and flexible. An entire array, including instrumentation, can be stored in a box and deployed by hand. A method was devised which enabled unlimited lengths of rope, cable, or complete arrays to be positioned and later retrieved by any ship having a powered capstan.

The instrument required is a large, "V" grooved sheave designed for attachment to a powered capstan. The line can be fed by hand from a box, around the "V" puller, over a fair lead sheave, and attached to an anchor or any other fixture. The hard neoprene or polyurethane groove of the powered sheave grips the rope so completely that it becomes very easy to hand feed out of, or into, a storage container. This method was used on actual installations of arrays (see section IV-B on Span 3) and was completely successful.

Figure 22 depicts the sheave, which is constructed of a number of neoprene sections (manufactured by Gearhart-Owen Industries). These parts are stock items ("V" Groove Segment 7000-0000-062) and are relatively inexpensive. For the sheave under discussion, total cost of parts amounted to about $500.00. The thirteen neoprene sections are sandwiched and bolted between two 0.95 cm aluminum plates that are 1.53 meters in diameter. Assembly and disassembly are simple tasks that can be performed in less than two hours. The plate circles are halved for easy storage and shipment.

E. Conclusions

Various percentages of breaking strength can be achieved with different choices of end fittings. Carefully applied eye splices, however, are the best possible choice for the following reasons:

- Can be made up in roughly two hours; no waiting for an epoxy cure.
- Will develop 100 percent of the cable break strength.
- Doubles the number of strength members at the bitter end.
- No point of sudden change in moment of inertia.
- Slight amount of strand slippage in splice allows better load sharing in the strands.
- Easily adaptable to various conductor/strength member arrangements.
- Inexpensive.
- Light weight.
- Splice can be applied at the bitter end or mid-cable without disturbing any of the cable strength members or conductors.

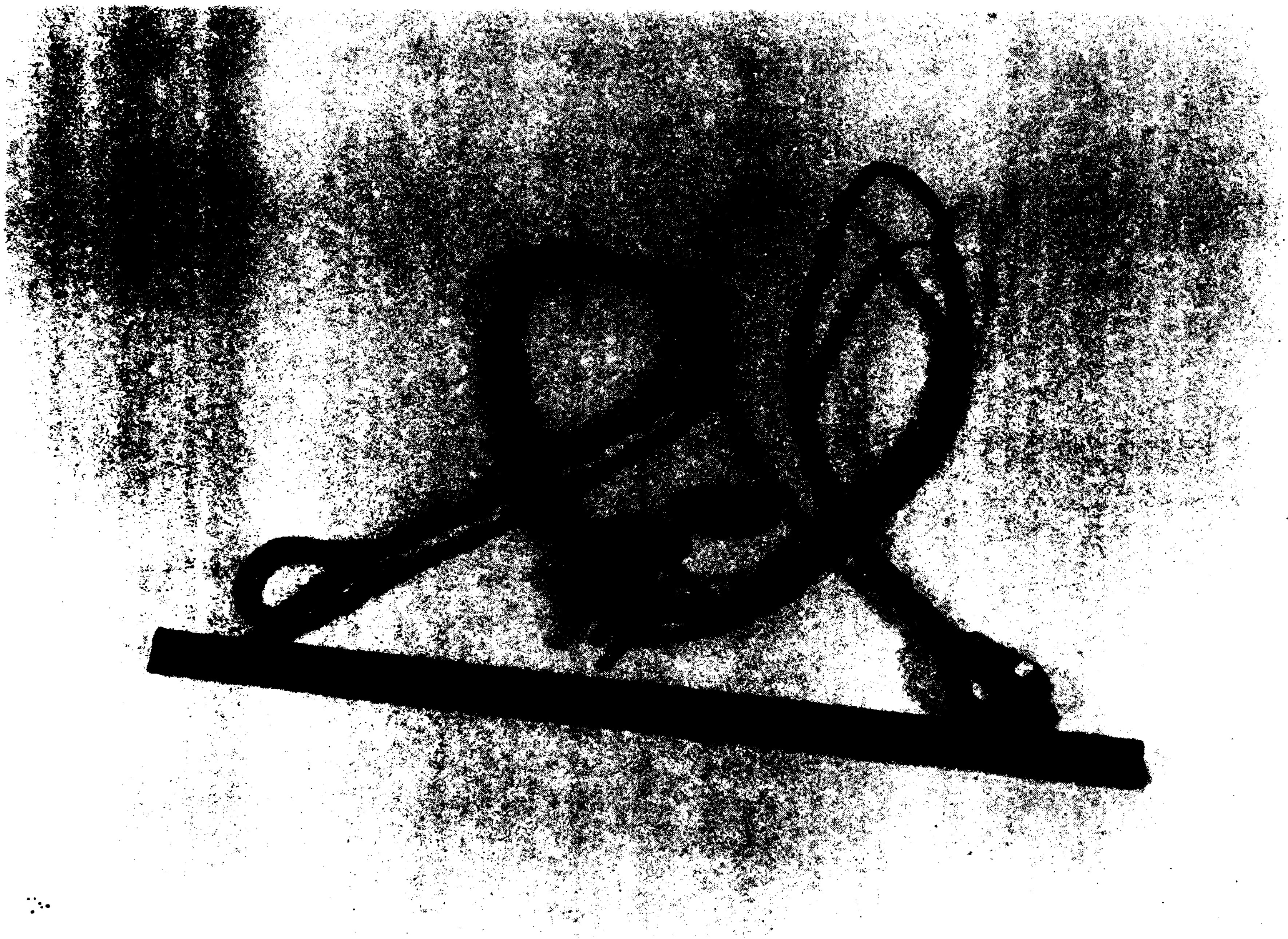


Figure 40. Two End of a Braided Rope, Each with an Eye Splice, Braided Together to Represent a Mid-Line Splice

XI. OTHER DEVELOPMENTS

A. Naval Underwater Systems Center Uniline Bending Test

In April 1976, a bending fatigue test was performed on one 37.8 meter length of 3.8 cm diameter parallel lay Kevlar 29 rope (Seaman, 1971). The rope, supplied by Wall Rope Works, was neoprene impregnated with a bonded nylon jacket, hung over a 3.96 meter diameter fixed sheave (this supplied a D/d ratio of 104:1), and tensioned to 325.6 kilonewtons, or 40 percent of BS, with a large pendulum weight. When the load is set in motion, the ensuing swing causes the cable to wrap and unwrap over the sheave, fatiguing the fibers. In this case, the arc of travel was 36° around the sheave, which actually worked a 1.6 meter length of line. Cycling continued for 10 days with 250 start-up swings; the cable failed abruptly after 162,016 cycles.

Several steel cables which had approximately the same diameter were compared for number of cycles to failure under similar conditions. Figure 41 shows a plot for bending cycles to failure vs. percent of break strength. The Kevlar rope compares favorably with the plotted steel cables.

B. Coaxial Electro-Mechanical Kevlar 29 Cables-Braid vs. Serves

This section discusses the testing of two constructions of aramid fiber strength member electromechanical coaxial cables developed by United States Steel Corporation in late 1974 (Felkel, 1976). Cable 1 was a double pass, Kevlar-braided design with a rated breaking strength of 44.5 kilonewtons. Cable 2 was a double reverse, Kevlar-wrapped design with a rated breaking strength of 35.6 kilonewtons. The test plan for these cables was to: determine cable elongation from zero to 1/2 of rated break strength; simulate load surges by tensioning to loads of 1/2 of rated break strength, and releasing as rapidly as the equipment will permit while monitoring conductor continuity; and cycle each cable to destruction over sheaves while under 4500 newtons tension.

1. Cable Elongation

A 14.9 meter length of Kevlar-braided coaxial cable was slowly loaded to 22.25 kilonewtons (1/2 of rated breaking strength), while recording the elongation (Figure 42).

Run Nos. 2 and 10 are in close agreement, indicating that much of the initial structural stretch has taken place and the cable has settled to the point where stretch with tension becomes repeatable, and therefore predictable. Using Run No. 2 as a standard, stretch at 50 percent of rated breaking strength was 1.32 percent, or 4.29 meters per 304.8 meters of cable. This elongation compares to 0.65 to 0.75 percent for a normal double steel armored cable.

A 14.9 meter length of Kevlar double-wrapped cable was slowly loaded to 184.4 kilograms (½ of rated breaking strength), while recording the elongation (Figure 43).

Run No. 1 showed an elongation of 1.71 percent at 17.8 kilonewtons. Upon releasing this tension, a permanent elongation of about 6.35 cm resulted in the test sample. This is equivalent to 0.4 percent permanent elongation.

Run Nos. 2, 3, 4, and 5 were virtually identical, and, as for Cable 1, Run No. 2 will accurately predict the elongations that will occur in service at any given tension up to 17.8 kilonewtons. Using Run No. 2 as a standard, stretch at 50 percent of rated breaking strength is 1.0 percent; this is less than the braided model. One reason for the reduced elongation of the wrap as compared to the braid is the smaller lay angle of the wrap (16.3°) as compared to the braid (23°).

2. Dynamic Loading

A 13.11 meter length of braided cable was tensioned at 22.25 kilonewtons as rapidly as possible and released as rapidly as possible. The conductors were monitored for continuity throughout the test. Continuity was lost on the 20th cycle. Careful examination showed that the central conductor had kinked and broken (Figure 44). Further, numerous kinks were observed in the return conductors. Several of the individual wires of this wrap had broken at points of severe kinks, but total continuity of the return conductor was not lost.

The above test was repeated on a second sample. In this test, continuity was lost on the 62nd cycle. Observations identical to the first test were recorded.

The procedure for the wrapped cable was the same as for the braided cable except that a total load of 17.8 kilonewtons was the goal. No loss of continuity was observed in 100 cycles. When tension was raised to 20 kilonewtons for 10 cycles, one of the end connections broke; but, once more, no loss in conductor continuity was experienced.

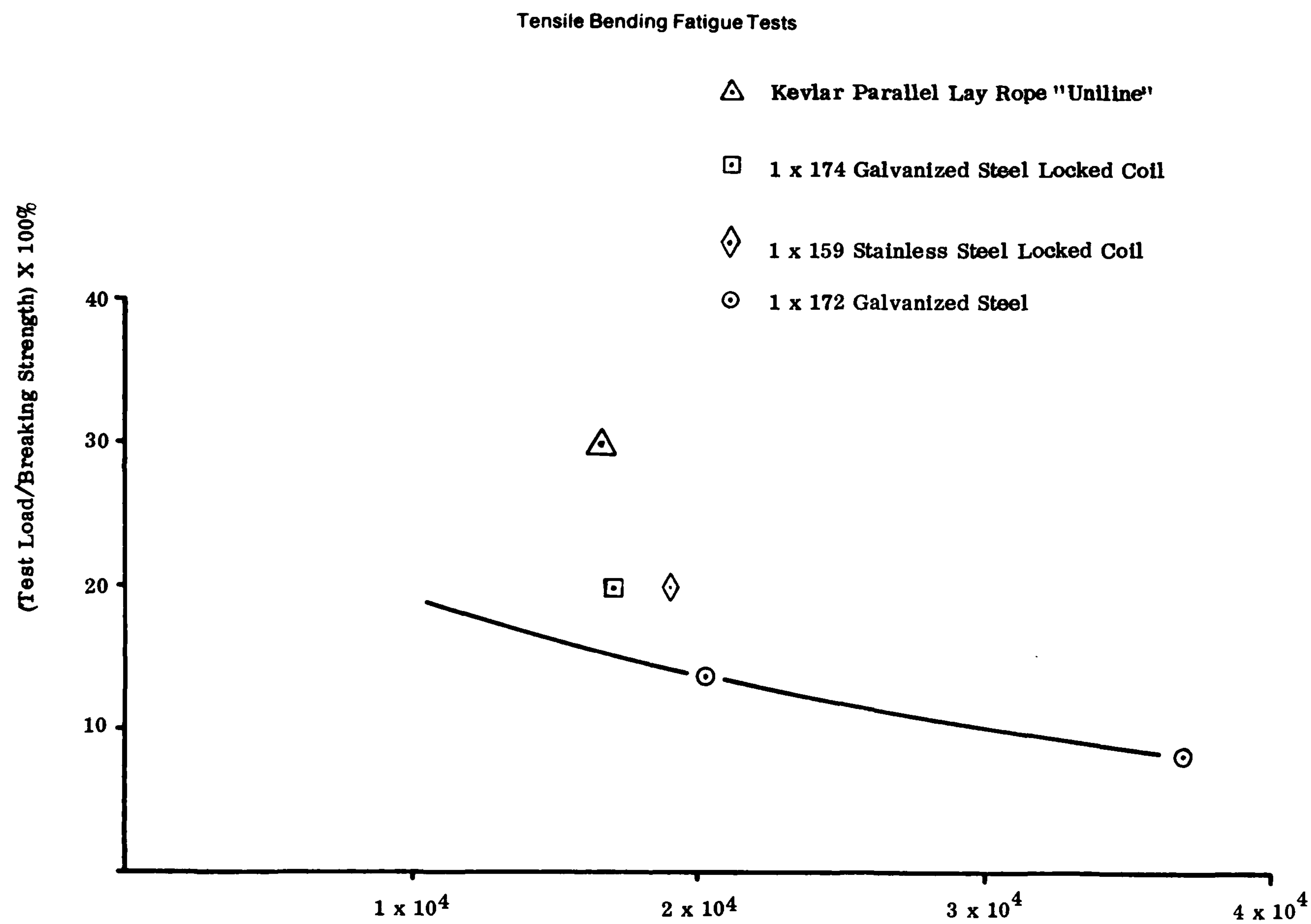


Figure 41. Bending Cycles to Failure for 3.8 cm Diameter Ropes Over a 3.96 m Diameter Sheave

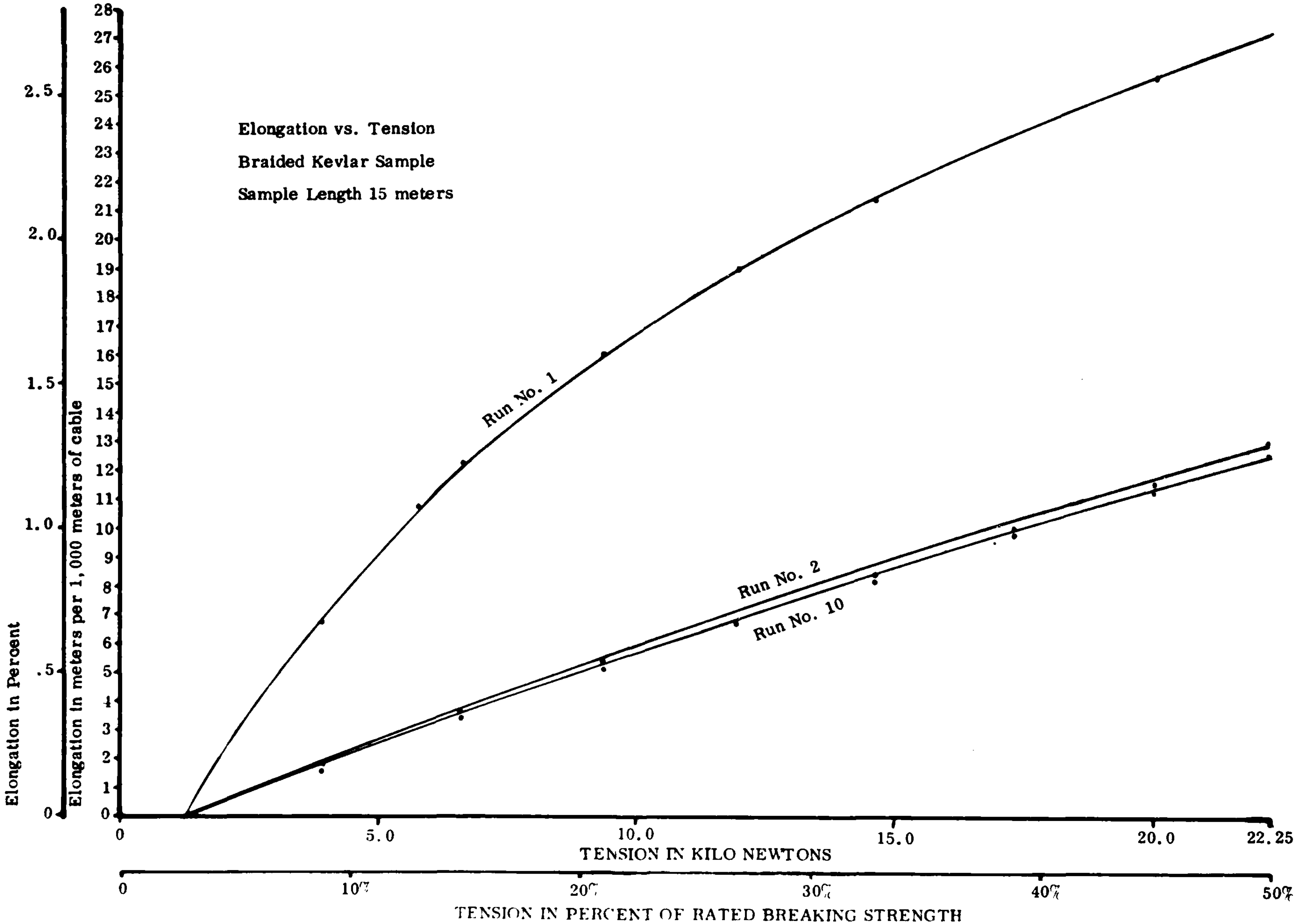


Figure 42. Load-Elongation Curves for Braided Kevlar Cable

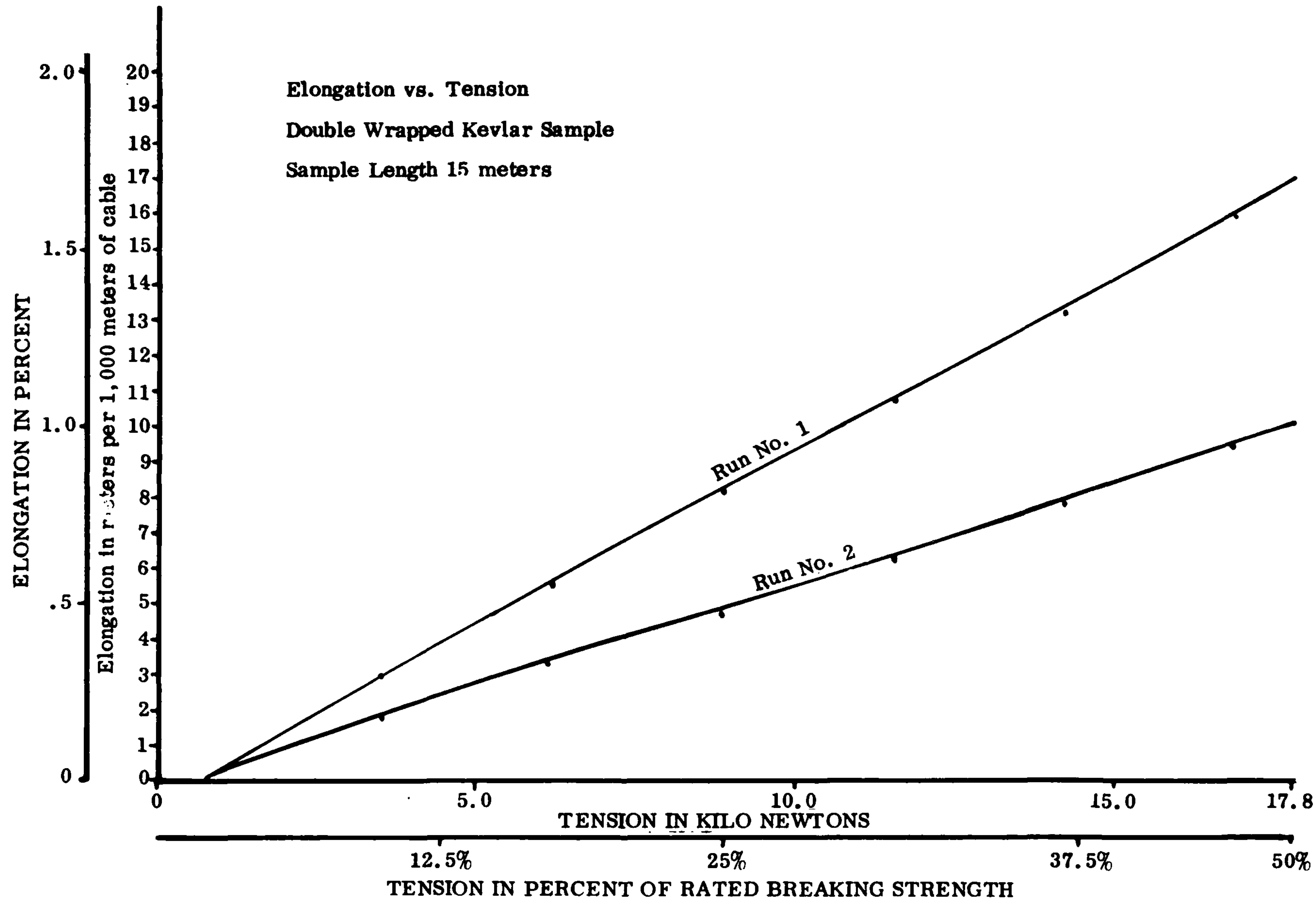


Figure 43. Load-Elongation Curves for Served Kevlar Cable

Figure 44. Coaxial Cable Failure Mode

In this test, the first observation is that the wrapped conductor fared better than the braided one. This could be predicted from a review of the stress/strain curves (Figures 42 and 43). These graphs revealed that the braided cable stretched 1.32 percent, while the wrapped cable stretched only 1.01 percent at 50 percent loading.

A 0.9 meter section was cut out of the wrapped sample and examined. This examination revealed three comparatively small kinks in the return conductor, but no kinking of the central conductor was noted.

Other conclusions reached on the basis of this test are:

1. Loading of Kevlar-strengthened coaxial cables should be held far below one percent elongation unless special designs are incorporated in the coaxial cable (See Section XI F).
2. The development of a more resilient central conductor is recommended if Kevlar is used.
3. The copper conductor outer wrap might have performed better if a higher angle (shorter lay length) were used. An application angle of 40° instead of 20° is suggested.

Further experimentation was recommended to ascertain "safe" operating loads, and particularly to develop and test extremely resilient central conductors—possibly sash cord types, new types of alloy conductors or both in combination (See section III).

3. Bending Tests

The object of this test was to determine the ability of the Kevlar cables, both braided and wrapped, to withstand flexing over sheaves under a tensile load. This test was intended to simulate the paying-off of a tow cable over sheaves.

Each sample was in contact with the pulley for 110°. The tension was fixed at 4450 newtons, which represents approximately 10 percent of the rated break strength of this cable. One complete cycle included a 1.22 meter movement in one direction, plus a 1.22 meter movement in the reverse direction. No attempt was made to monitor conductor continuity.

The braided cable broke in 4882 cycles. The mode of the break appeared to be almost complete disintegration of the Kevlar.

The wrapped cable broke in 2235 bending cycles. Early in the cycling, 72 ends of Kevlar in the outer wrap began bunching together, causing the configuration of the sample to take on a "spiral" appearance.

The braided Kevlar cable fared better than the wrapped; also, this test result is almost entirely independent of the core configuration. In other words, the weakness displayed would affect unfavorably both coaxial and multiconductor cables.

4. Conclusions

1. The self-abrasion of this design Kevlar cable makes it a *poor* candidate for any service which entails an appreciable amount of tension cycling over sheaves. An effort was made to improve the abrasion resistance, which, at this writing, has proved feasible.
2. The elongation characteristics made Kevlar a risky choice when used with a coaxial or single conductor core. In this respect, Kevlar seems to have some merit if the surge tensions can be kept to a low percentage of the break strength of the strength member. Improvement in this area appeared to be a possibility if an effort was made to develop more resilient central and return coaxial conductors. This has been accomplished and is described in Chapter III.
3. The braided construction was easier to manufacture, especially in long continuous lengths.
4. The double reverse wrapped construction exhibited considerable torque.

C. Fairings

1. Array and Mooring Lines

Strumming takes place whenever a long cable is placed in a fluid flow normal to the cable. Forces normal to both cable and flow are induced, and are a result of flow separation in the downstream wake. Large, regularly shedded eddies form into a flow pattern which is termed a vortex street. The vortices generate a corresponding alternating lateral force which produces the oscillations known as strumming.

For suspended hydrophonic arrays, low-frequency strumming noise is created by direct mechanical coupling of the oscillatory cable motion to the attached hydrophones, and also by acting as a low-frequency sound source that propagates sound directly into the water. These cable vibrations can seriously degrade the mechanical performance of the system by increasing cable drag and producing long term fatigue failures. The distinct possibility that fishbite damage is precipitated by strumming also exists.

The vortex shedding frequency is directly proportional to the Strouhal number over a certain range of Reynolds numbers, and is a function of the cable diameter and the stream velocity. When the natural frequency of the cable or segment of the cable (which is a function of the cable length, tension, and mass) is near the vortex shedding frequency, resonance will occur; thus, large amplitude vibrations will be produced. The natural frequency can be controlled in the design stage by varying one of three parameters. However, a rather large amount of change in the length, tension, or mass causes a significant change in the fundamental frequency.

Installation of either streamlined fairing, which keeps the flow laminar about the cable; a trailing splitter plate, which obstructs and reduces the vortex street; or a fairing designed to destroy the cable symmetry, thereby eliminating the alternating side forces, are methods of reducing strumming. The major problem with such methods has been the cost and operational consequences of totally fairing long cables on the basis of existing fairing designs and cable-attachment techniques.

Various methods have been used on hydrophone arrays to eliminate or suppress strumming interference. These include utilizing acceleration-canceling and/or low-frequency-insensitive hydrophones, and decoupling the hydrophone from the cable by using isolation-mounting techniques. Unfortunately, these methods only treat the symptoms and generally result in restrictions on hydrophone depth placement, low-frequency measurements and handling characteristics.

In the initial phase of this program, a fairing was developed that had to meet three basic design requirements:

(a) Cost Less Than a Dollar Per Cable Foot

During the development of Kevlar cables, it became apparent that a fringe-type fairing could be incorporated into an outer braided jacket during braiding, and should significantly reduce the cost through the one-step automatic process. Wall Rope, under contract to produce the prototype cables, developed a technique to incorporate tufts of yarn (e.g., polypropylene up to 15.24 cm long) at 2.54 cm spacing in the cable outer braid. In addition, different colored tufts can be inserted at selected intervals or locations while the cable is under tension in order to permanently and clearly mark length intervals or sensor-attachment locations. Such marking is extremely advantageous during subsequent array assembly and deployment. The current price of this fairing is between $0.50 and $1.00 per foot, depending on the length and diameter of the cable.

Concurrent with the efforts at Wall Rope, a small contract was issued to Prodesco, Inc., Parkasie, Pennsylvania, to develop a fabric-backed fringed fairing tape that could be helically wound around a cable and attached to produce a fringe fairing. The polyester tape body is 1.58 cm wide and has 7.62 cm polypropylene tufts protruding from each site. The resulting material is available in 213.4 meter rolls, and the cost of the tape is approximately $1.64/meter.

(b) Would Not Inhibit Array Handling or Increase Cable Size or Weight

Three lengths of 1.68 cm diameter, double-armored steel tow cable were overbraided and faired with the Wall Rope fringe fairing (Figure 45). One length was used to tow a 226.8 kilogram sound source at depths to 152.4 meters for over 1600 kilometers at speeds up to 8 knots in the summer of 1974. A second length was used by WHOI to tow a lighter source in a similar manner. In these applications, strumming suppression is used to prevent cable and end-fitting fatigue. Because these tow cables can be reeled, unreeled, shipped by air and handled many times, considerable logistic, winch, and labor savings are realized by using this type fairing in lieu of the more cumbersome rigid-vane-type fairing previously employed for these applications. Obviously, more development is required (and warranted) to optimize the fairing design for these low-speed tow applications.

Another 9144 meters of 1.90 cm-diameter, 18-conductor, 62.3 kilonewton break strength Kevlar 29 cable with 1.02 cm long polypropylene tufts spaced 2.54 cm apart has been produced. Acoustical and mechanical performances have been excellent in both a 4772 meter WHOI array and a 1402 meter NUSC array. No strumming was observed in the acoustic data during several deployments, and no cable handling problems were encountered.

(c) Would Reduce Strumming in Currents of Less than Two Knots

In Spring 1974, WHOI carried out a fairing evaluation program (funded by ONR) in which various fairing samples were subjected to tidal currents off a pier (Davis, 1974). Two 18.29 meter composite cable samples, one faired and the other identical, but unfaired, were tensioned vertically to approximately 4450 newton load. Polyurethane ribbons on a 0.95 cm-diameter double-armored steel cable and fringe fairing on a Wall Rope Uniline cable were the principal samples. A great deal of scattering was observed in the bare-cable acceleration data because the cables were not well isolated from outside vibrations, and there was some doubt about the current velocity measurements. The significant feature is that above 0.2 knots of current, considerable strumming was present in the bare cable and increased rapidly with velocity. On the other hand,

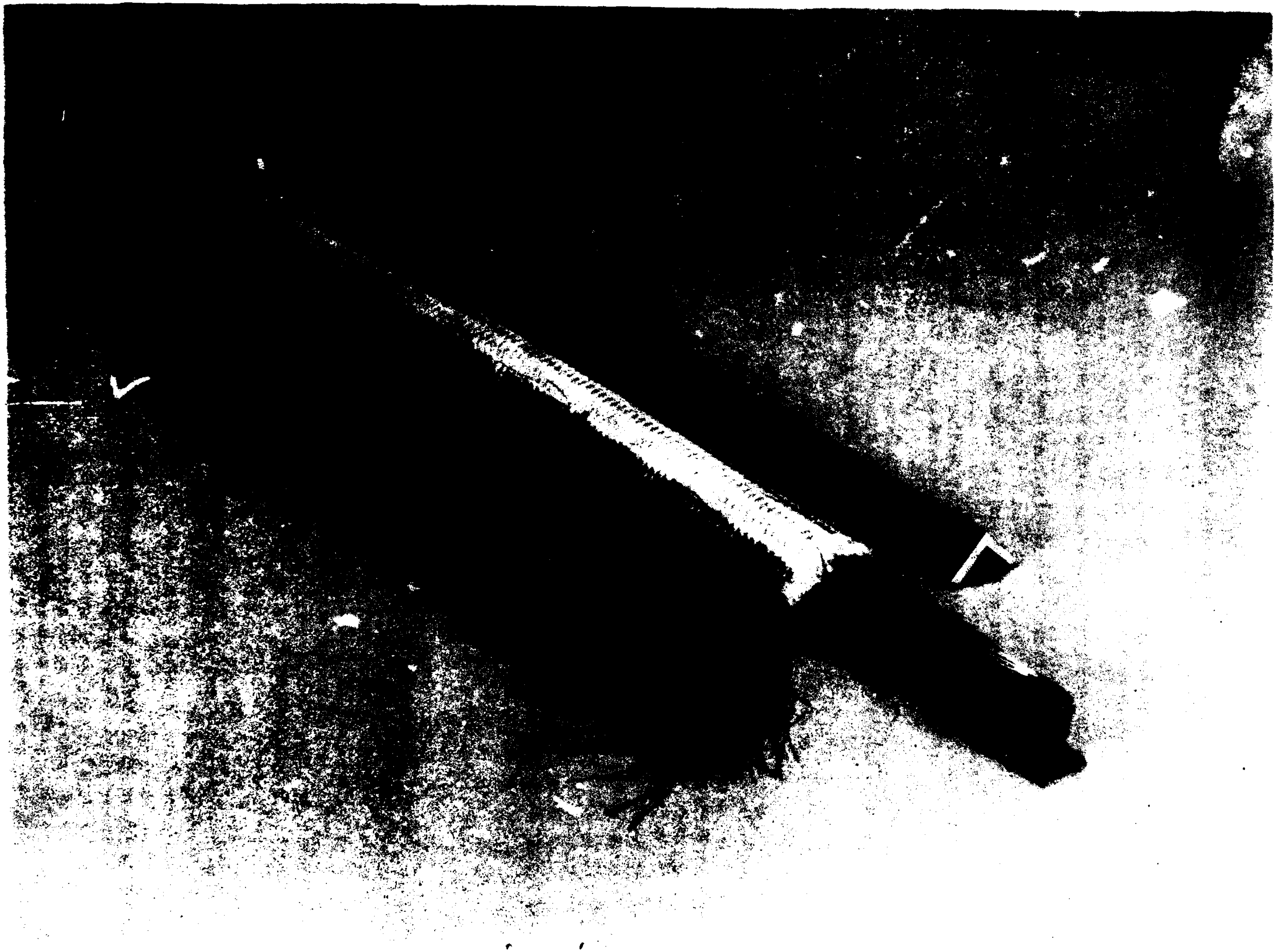


Figure 45. Double Armored Steel Cable Overbraided with Nylon Jacket and Fairing to Reduce Strumming

various types of fairing significantly reduced vibration within the range of currents measured. Furthermore, the data show that fringe fairing on the Kevlar Uniline cable produces the quietest cable and appears to be quite effective at lower velocities.

In 1975, a series of strumming experiments was conducted (funded by ONR) on five different cables near Castine, Maine (Kan, 1974). The tests took place on a sandbar which was exposed at low tide. As the tide came in, the current velocity increased from zero to a maximum of 0.9 meter/sec. The 22.9 meter samples were horizontally suspended about 0.61 meter above the sand. At high tide, the cable was under almost 2.44 meters of water.

Table 12 lists both the physical characteristics and measured values of the five different cables tested in this experiment: (a) Sampson "Blue Streak" braid; (b) U.S. Steel 3 x 9 torque balanced, wire rope; (c) Philadelphia Resins 7 x 7 Kevlar rope with polyurethane jacket; (d) Philadelphia Resins braided Kevlar electromechanical cable with anti-strumming fairing; and (e) same as (d) but fairing removed.

The measured Strouhal numbers for the "Blue Streak" and unfaired electromechanical cable were approximately .17, which agrees with measurements from other sources. The .21 observed Strouhal number for the Kevlar twisted rope has not yet been explained. With respect to the anti-strumming cable, frequency of vibration was found to be independent of tension at high current velocity. The anti-strumming fairings decreased the cable amplitudes by 30 percent, but increased the effective diameter by 26 percent, thereby increasing the drag. Results seemed to indicate that the anti-strumming design was not completely effective. Because the results pointed the direction, but were not conclusive, ONR sponsored a third series of experiments which were completed in the summer of 1977 by Professor J. Kim Vandiver of Massachusetts Institute of Technology (MIT).

During June and July 1977, additional field tests were conducted on the sandbar near Castine. Cables with four different types of fairing were evaluated and compared to cables with no strumming suppression devices. The tidal currents ranged from 0 to 0.76 meter/sec. and provided a Reynolds number range from 0-8000 for the 0.635 cm diameter cables.

The cables tested were:

1. Wall Rope Works
   - (a) 0.635 cm diameter Kevlar Uniline Cable with Nylon fringe fairing 7.6 cm long, 1.9 cm spacing
   - (b) 0.635 cm diameter polyester Uniline Cable with Nylon fringe fairing 7.6 cm long, 1.9 cm spacing.
     - (1) Tested with complete fairing
     - (2) Tested with fairing trimmed to 5.08 cm long
     - (3) Tested with fairing trimmed to 2.54 cm long
     - (4) Tested with no fairing
     - (5) Tested with 7.6 cm long fairing but with 3.8/cm spacing.
   - (c) 0.635 cm diameter Polyester Uniline Cable with black polypropylene fringe 7.6 cm long, 1.9 cm spacing.
     - (1) Tested with full fairing
     - (2) Tested with fairing reduced to 3.81 cm long.
2. Philadelphia Resins
   - (a) PS29 EM1 Cable. This cable was 0.635 cm diameter and consisted of four electrical conductors surrounded by Kevlar and protected by a woven Dacron jacket.
     - (1) Approximately 1.9 cm long soft polyester fringe wrapped helically around cable.
     - (2) Approximately 1.9 cm long stiff polypropylene bristles wrapped helically.
     - (3) Tested with no fairing.
3. Cortland Line Company — 0.635 cm diameter jacketed Kevlar.
4. 0.476 cm wire rope

As previously mentioned, the report has not been completed, but several conclusions have been drawn by Professor Vandiver.

1. All the anti-strumming materials increase the damping of a vibrating cable, and thereby decrease strumming amplitude.
2. The Wall Rope fairings prohibit strumming at current velocities less than approximately 0.305 meter/sec. and allow strumming under lock-in conditions from 0.152 meter/sec. Strumming is substantially suppressed at frequencies away from lock-in. Trimming or thinning the fairing generally increases the strumming response. The polypropylene fringe is superior to the nylon in strumming suppression.
3. The two Philadelphia Resins samples exhibited grossly different behavior. The soft polyester fuzz was relatively ineffective. The stiff polypropylene bristles eliminated all strumming in currents up to 0.61

Table 12. Summary of Cable Strumming Data (From July 1975 Experiments)

	(a) Sampson Blue Streak	(b) USS Wire Rope	(c) Phillystran Kevlar	(d/e) Anti Strumming Kevlar w/wo Fairing
Diameter (cm)	1.0	0.7	1.2	.4
Linear Density in Air (gr/m and lb/ft)	64.78/.0435	108.3/.073	113.2/.076	---
Overall Length (meters)	23.3	23.3	23.3	23.3
Current Range (m/sec)	.08-.64	.06-.73	.08-.67	.49-.64
Reynolds No. Range	660-5200	360-4200	800-6850	1500-2100
Frequency Range (Hz)	1.3-11.3	2.2-18.3	1.5-12.1	14.3-21.3/19.0-27.8
Strouhal Range	.16-.18	.16-.18	.20-.22	.12-.13**/.17
Tension Range (n)	70-230	60-580	110-450	70-80
Velocity During Tension (m/sec)	0.43	0.61, 0.7	0.64	---
Typical Amplitude (O-P diameters)	.4-17	.4-.7	.3-.5	.5*/.5-.7*
Traversal of Accelerometer	No	Yes	Yes	No

**Based on unfaired diameter

meter/sec. Recent qualitative observations show that this cable exhibits strumming behavior at speeds of 3 to 4 knots.

D. Wet Tension Fatigue

Shortly after the announcement by DuPont in July 1972 that Kevlar would be made commercially available for cable applications, NUSC contracted to test the material for undersea usage (Swenson, 1975). The fibers were subjected to several tests which included long term creep in air and in water. Figure 46 illustrates the results of these tests on the Kevlar for a period of 720 days. From these initial measurements, results showed that creep was not a significant problem. Kevlar is load dependent and results in less than 0.2 percent elongation per year in the expected load ranges. The slight difference between the wet and dry elongation results is attributed to the lower tension in the wet samples as a result of friction in the pulleys of the horizontal test apparatus. These tests continued until mid-1975 with no change in the initial findings.

Both DuPont (Riewald et al., 1975) and the Naval Air Development Center (Brett et al., 1975) conducted similar creep tests with similar results. DuPont tested samples loaded to 50 percent of ultimate break strength (UBS) with less than 0.2 percent elongation both wet and dry (Brett, 1975). NADC's short-term creep tests to 50 percent of rated break strength also indicated negligible creep after a small initial elongation (Chiao et al., 1973). These results indicate that creep is not a problem, and that creep properties, when wet, are the same as when dry.

Stress rupture or static fatigue tests are conducted in the same manner as the long-term creep tests; however, the time required to break the specimen is recorded rather than the specimen elongation. The earliest and most comprehensive study of Kevlar stress rupture properties was performed at Lawrence Livermore Laboratory in California. (Chiao et al., 1973). The long-term performance of Kevlar impregnated with an epoxy matrix was compared to an S-glass/epoxy composite. The report is an excellent statistical study which provides a failure probability at various percentages of operating stress levels for long-term usage. Although most of the data were taken at loads greater than 70 percent of ultimate fiber tensile strength, the curves are extrapolated to predict that, if a very low failure probability is expected, the fiber stress levels must be below 70 percent. NADC (Brett et al., 1975) later supported these results by observing that there was no evidence of static fatigue at loads less than 70 percent of ultimate tensile strength. The report indicates that a point of long-term stability is reached at about 75 percent of ultimate, however, these tests were performed under ideal conditions. Therefore, the more realistic conclusion is that the fiber should not be loaded above 70 percent of UBS.

The Naval Oceanographic Laboratory is presently sponsoring a series of combined creep and static fatigue tests on 0.635 cm diameter Kevlar Uniline ropes. The information published on strands is not directly related to the ropes because nonuniformities in rope construction can lead to localized overloading. The parallel construction was chosen because it minimizes any problems caused by fiber crossovers. More important, the Navy is now utilizing this line, thus, the planned data is needed to establish long-term, safe, mooring loads. Eight ropes have been tensioned to date; four have failed. All failures have been tensioned at loads greater than 70 percent of ultimate. From the data shown in Figure 32, it is obvious that the maximum tensile load must remain below 70 percent for long-term loading. This same series of tests is planned for braided ropes.

According to chemical studies by DuPont, Kevlar has good resistance to a wide range of solvents, oils, greases, and waters. In order to determine if water under high pressure had any effect on the material's physical properties, NUSC conducted a series of submergence tests in 1973.

Coiled samples were subjected to 10,000 psi of water pressure for a period of 20 days, and then tensioned in a water bath at loads from 10-50 percent break strength for an extended period of time. The approximate 10 percent strength increase gained by urethane impregnation of the fibers was lost due to water pressure treatment, meaning that Phillystran had reverted back to the original Kevlar yarn strength. However, no strength decrease was observed in the basic Kevlar. These tests were further extended by repeating the pressure tests with the strands under 15, 20, and 25 percent of UBS by spring loading in a test frame and inserting the assembly in a pressure facility. Again, no significant strength loss was observed. Because of these results, and because of DuPont's contention that Kevlar was unaffected by sea water, additional tests were deemed unnecessary.

However, in the spring of 1976, WHOI (Walden, 1976) furnished a preliminary report indicating a significant reduction of strength in experimental Kevlar mooring lines used on both surface and subsurface moorings. Results are discussed in Chapter V. Two buoys, each using Kevlar fiber lines, were deployed in shallow-water test surface moorings in February 1974. One was found ashore after 26 months. Upon recovery, WHOI tested the severed line and implied a 62 percent reduction in the break strength of the rope

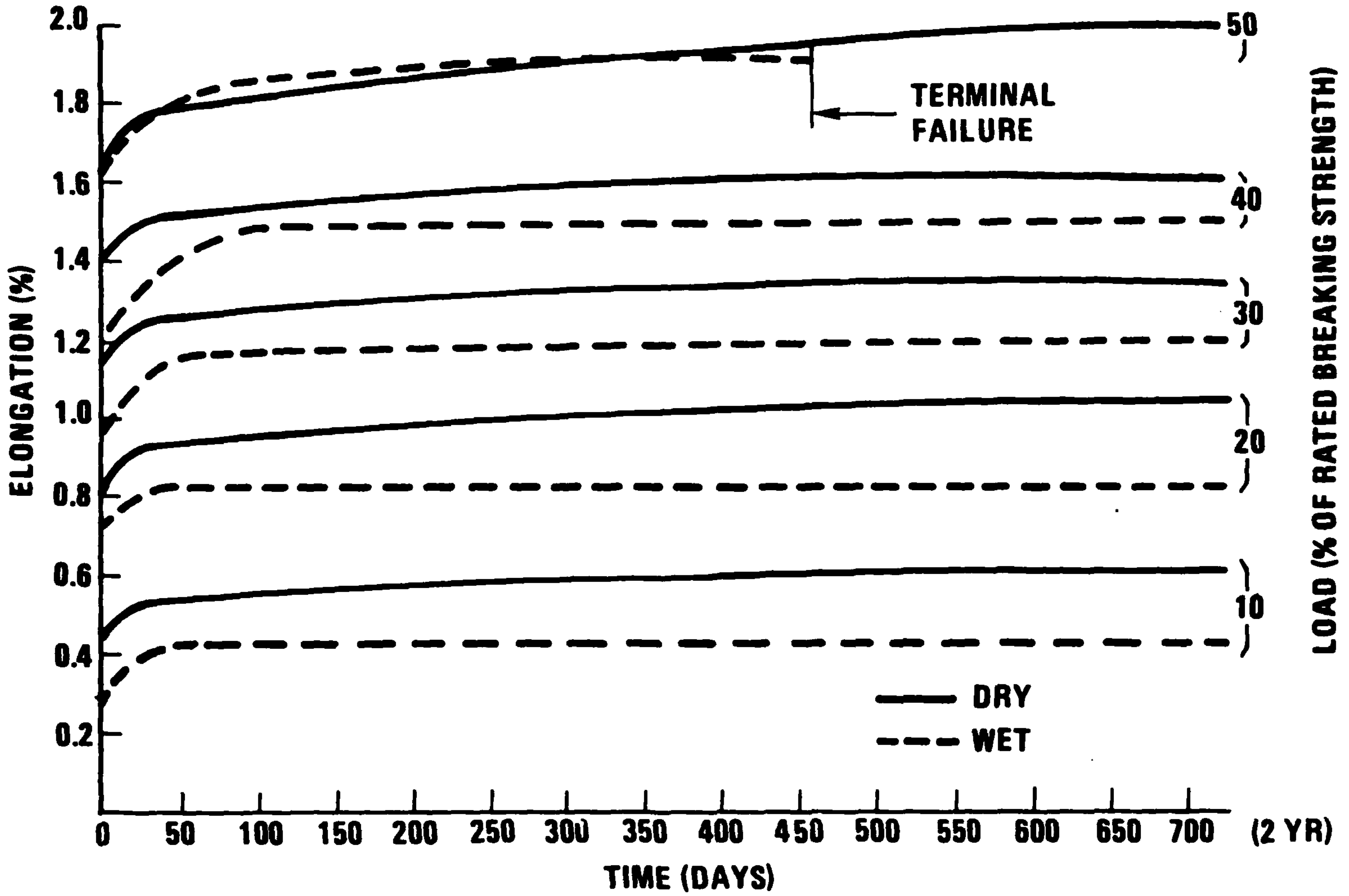


Figure 46. Results of Creep Measurements for Kevlar Fiber (1500 Denier Yarn)

sample. The second mooring was then recovered after a total of 29 months on station. Samples of both lines were sent to DuPont and to the rope's manufacturer (Wall Rope Works) for further evaluation. DuPont found, at most, a 20 percent strength reduction in the first rope; however, much of this was thought to have occurred as the rope was beaten about in the surf. In addition, the break indicated a cut rather than fiber failure. Strands removed from the second rope (29 months) showed only a 5 percent strength reduction. This was after an estimated ten million tension-tension cycles while the load averaged about 12 percent of UBS.

The subsurface test moorings, also set by WHOI, consisted of two ¼ inch parallel fiber ropes, one manufactured by Wall Rope Works, the second by Columbian Rope (Bourgault, 1975). Four moorings were deployed for eight months with the tension in each leg equal to approximately 17 percent of UBS. Upon recovery, samples were tested and the remainder of the line was redeployed in two moorings; one tensioned at 33 percent of UBS, and the other at 45 percent UBS. They were recovered after four and three months, respectively.

The neoprene coated "Uniline" (Wall Rope) was reported to have lost about four percent of its strength after eight months at 17 percent of UBS. The Columbian rope averaged 14.5 percent strength reduction

After an additional three months at sea, the "Uniline" had a reported 36 percent strength reduction loaded at 45 percent of UBS, while the Columbian rope averaged a 31 percent strength reduction. Severe tangling occurred upon mooring recovery, and the Columbian rope suffered hockling because of its unusual construction. DuPont tested the fibers removed from various locations within the Uniline rope and found only a five percent strength reduction. However, DuPont did not test any fiber specimens from the Columbian rope.

WHOI's observations were also reinforced with data released by NUSC. Their report indicated a strength reduction in a Kevlar cable used to tether a surface-following buoy which was moored in a depth of 1500 meters for a period of four months. After buoy recovery, tests performed by NUSC on the cable indicated a 25 percent decrease in the rope's break strength.

These two reports caused apprehensions about Kevlar's utilization in sea water. Also, doubt was thrown upon the preliminary experiments because the low sample number tests had been conducted in tap water, not salt water.

Upon receipt of these reports, the decision was made that a new series of tests which included the effects of pressure, tension, and immersion in sea water on various types of tension members were necessary. The planned experiment, similar to the original, but more extensive, involved samples of each Kevlar fiber marketed by DuPont, including polyurethane impregnated Kevlar, two types of DuPont Dacron*, samples of DuPont nylon, and three types of steel wire. Five types of Kevlar 29 and five types of 49 yarns (nominally 1500 denier) were tested with two turns/2.540 cm in the yarn. The nylon and Dacron yarns were t ted at three turns/2.540 cm. Twist was added to the yarn to facilitate handling and testing.

A frame of brass and lucite was constructed which could accommodate 50 samples, each 1.5 meters long (Figure 47). The various materials, previously tested by DuPont to determine ultimate tensile strength, were installed in the frame. The fiber was terminated by taking a number of wraps around a cylindrical steel ring (D/d-24/1), concluding with a series of half hitches. This was then coated with urethane to prevent slippage. Each sample was placed in a series with a spring and a tensioning bolt, and individually adjusted. Two lengths of each fiber type were loaded to 20 percent of ultimate break strength and two lengths to 35 percent of UBS. Extreme care was taken during the whole procedure to protect the fiber from abrasion. Figure 48 depicts the arrangement at the spring termination. The completed frame was slipped into the lucite tube, filled with sea water (salinity = 31.9), sealed and inserted into a hydrostatic pressure tank. Total time under pressure was 2078 hours (88 days); however, because the pressure facility had to be used for other short-term experiments, the fibers were actually immersed and under tension for about 110 days. The pressure was cycled at least four times over the whole period. Upon completion, the water was drained and the assembly taken to DuPont's experimental fiber facility for careful testing. Two of the samples broke while immersed under load, but subsequent testing of the loose yarns did not reveal any significant strength loss. Both broke at the first bend of the termination, indicating an overstress at that point.

The two 1.5 meter lengths of each specimen type yielded eight tensile breaks, providing a sufficient sampling.** Concurrent with the wet tests, DuPont "in-air-loaded" selected samples for comparison purposes. They were tensioned at the same loads and for the same length of time as the immersed samples.

Table 13 is a list of the various fibers tested and respective break strengths. These data indicate that Kevlar aramid yarn does not lose significant strength in salt water under load and pressure (three months at 64 M Pa). Similar behavior was observed for the three steel wires and the Dacron polyester yarn, but, as expected, nylon yarn does have a moderate strength loss. Of all the Kevlar yarns tested, Kevlar 29 with rope finish is most

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**Tested under standard DuPont conditions - 75°F/55%R.H.

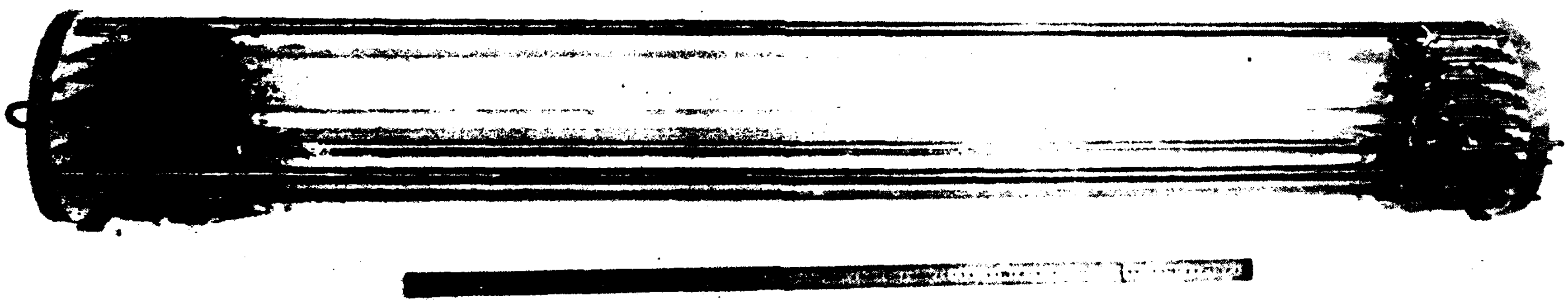

Figure 47. Strand Test Frame

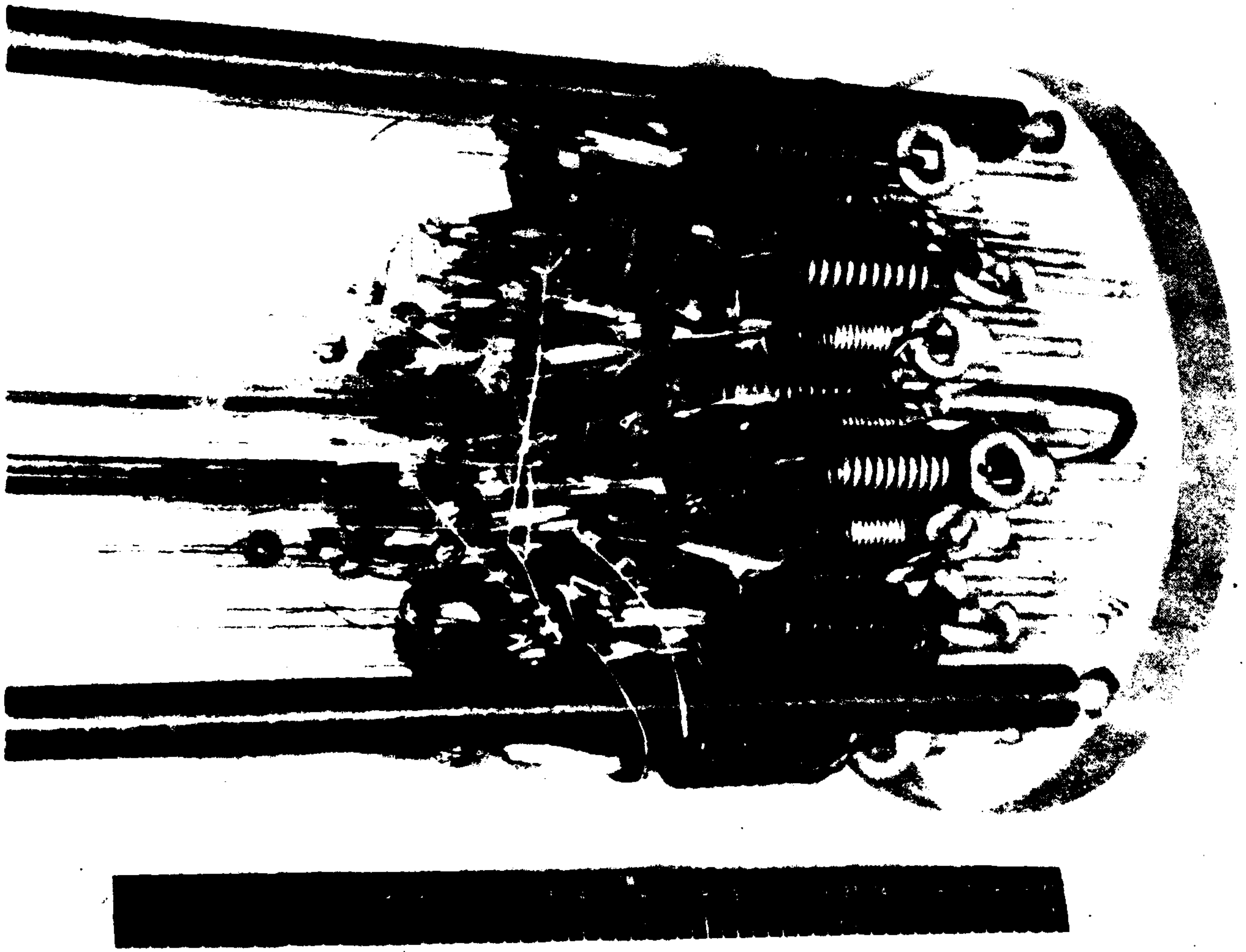

Figure 48. Strand Termination

suspect. Phillystran impregnated yarn (PS29-B15), also included in the immersion tests, has an average residual strength of 302 newtons after loading at 35 percent of break strength.

This information (Ferer, 1977) supports the contention that there should be no inherent strength loss due to salt water, and little or no loss under normal loading conditions. The study should remove most doubts about the ability of the aramid fiber to perform under static load in the marine environment. Obviously, damage due to internal or external abrasion is another potential problem.

E. Kevlar Rope Design Guide

Under the joint sponsorship of the Chesapeake Division and Code 032C of NAVFAC, a report about Kevlar aramid fiber was written, printed, and delivered in FY76 (Ferer et al., 1976). The title is "Design Guide for Selection and Specification of Kevlar Rope for Ocean Engineering and Construction."

The objective of this design guide was to present information for use in selecting and specifying Kevlar aramid ropes for ocean engineering and construction applications. This guide is based on available technical data which are representative of state-of-the-art knowledge of the material, rope design, manufacturing processes, test procedures, and application engineering. The following unique properties of aramid rope are discussed:

1. Very low stretch.
2. High tensile strength.
3. Very high strength-to-weight ratio.
4. Excellent fatigue resistance.
5. Good performance over large temperature range.
6. Low creep.
7. No shrinkage.
8. Minimum snapback hazard.
9. Good chemical stability.

The negative aspects of the fiber are also covered and include:

1. Low transverse modulus.
2. Self-abrasion of the fibers.
3. High material cost.

The various constructions available are compared with similar constructions of other rope materials (including wire rope) and comments are made on the relative merits of each for different ocean-engineering applications. The comparative data between aramid fiber rope and rope made from other materials are an aid in supporting objective decisions made by an engineer in selecting rope materials. Because cost factors are important considerations in the selection process, the relative cost of comparable ropes of various materials are established.

This guide also provides information on splices and terminations for aramid rope so that the engineer will understand joint efficiencies, reliability factors, and load constraints involved in selecting and specifying splices and terminations. Such service considerations as sheave sizing, abrasion, fake-down requirements, sharkbite protection, environmental exposure, and related application information needed to specify handling and protective requirements are discussed.

F. NAVSEA Kevlar Coaxial Cable Development Program

The objective of this three-year program is to develop and produce a reliable 8534.4 meter length of Kevlar reinforced coaxial electromechanical cable for an explicit use. An approach was taken to design, fabricate, and test pilot cables for problem definition; utilize these results to design, fabricate, and test prototype cables; and, with successful results, construct and test the production cable. This process was to be reinforced with mechanical modeling and stress analysis.

The major problem identified at the onset of this program was the copper fatigue problem of the center conductor associated with elastic elongation of the Kevlar strength members. Early concern was clearly validated in subsequent testing within this and other programs.

A second area of concern was the low bending life of the braided Kevlar cables. A braided Kevlar design was chosen to ensure absolutely no torque in the cable and for ease of manufacturing. However, abrasion between the Kevlar strands at cross overs and between layers limited the bending of the cable to an unacceptable lifetime. This abrasion has been significantly reduced by the use of strand impregnation, lubricants and separation tapes.

A third problem area is becoming more evident as the program nears the half way point: the ability to manufacture a continuous 8500 meter length at a reasonable cost and risk.

Table 13 Strength Loss Under Load in Sea Water or Air
(90 Days Exposure)

Material	Initial Strength N	Air Dead Loading 20% of RBS Strength N	Air Dead Loading 20% of RBS % Change	Air Dead Loading 40% of RBS Strength N	Air Dead Loading 40% of RBS % Change	Spring Loading in Salt Water (55 M Pa) 20% of RBS Strength N	Spring Loading in Salt Water (55 M Pa) 20% of RBS % Change (No. of Samples)	Spring Loading in Salt Water (55 M Pa) 35% of RBS Strength N	Spring Loading in Salt Water (55 M Pa) 35% of RBS % Change (No. of Samples)
"Kevlar" 29-Std Finish	334					334	0 (8)	334	0 (6)
"Kevlar" 29-Rope Finish	338	330	-2	338	0	321	-5 (7)	318	-6 (6)
"Kevlar" 29-Finish-Free	320					323	+1 (7)	323	+1 (8)
"Kevlar" 49-Std. Finish	310	310	0	320	+3	295	-5 (8)	300	-3 (5)
"Kevlar" 49-Finish-Free	271					263	-3 (8)	279	+3 (7)
Aluminized IPS. 17 mil	285	288	+1	288	+1	288	+1	288	+1
Stainless Steel. 16 mil	294	300	+2	300	+2	276	-6	303	+3
Double Galvanized IPS. 32 mil	863					880	+2		
Nylon - T-707	231	222	-4	213	-8	222	-4	218	-6
"Dacron" - T-67	94	93	-1	93	-1	91.5	-3	90.5	-4
"Dacron" - T-618	80					80	0	80	0

*One of the two samples broke during salt water immersion
(Tests performed by E. I. DuPont and Co.)

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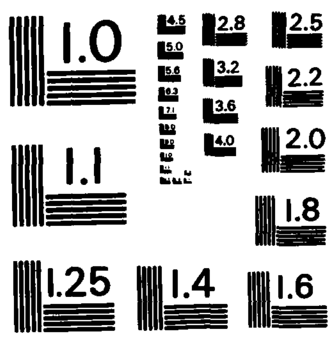

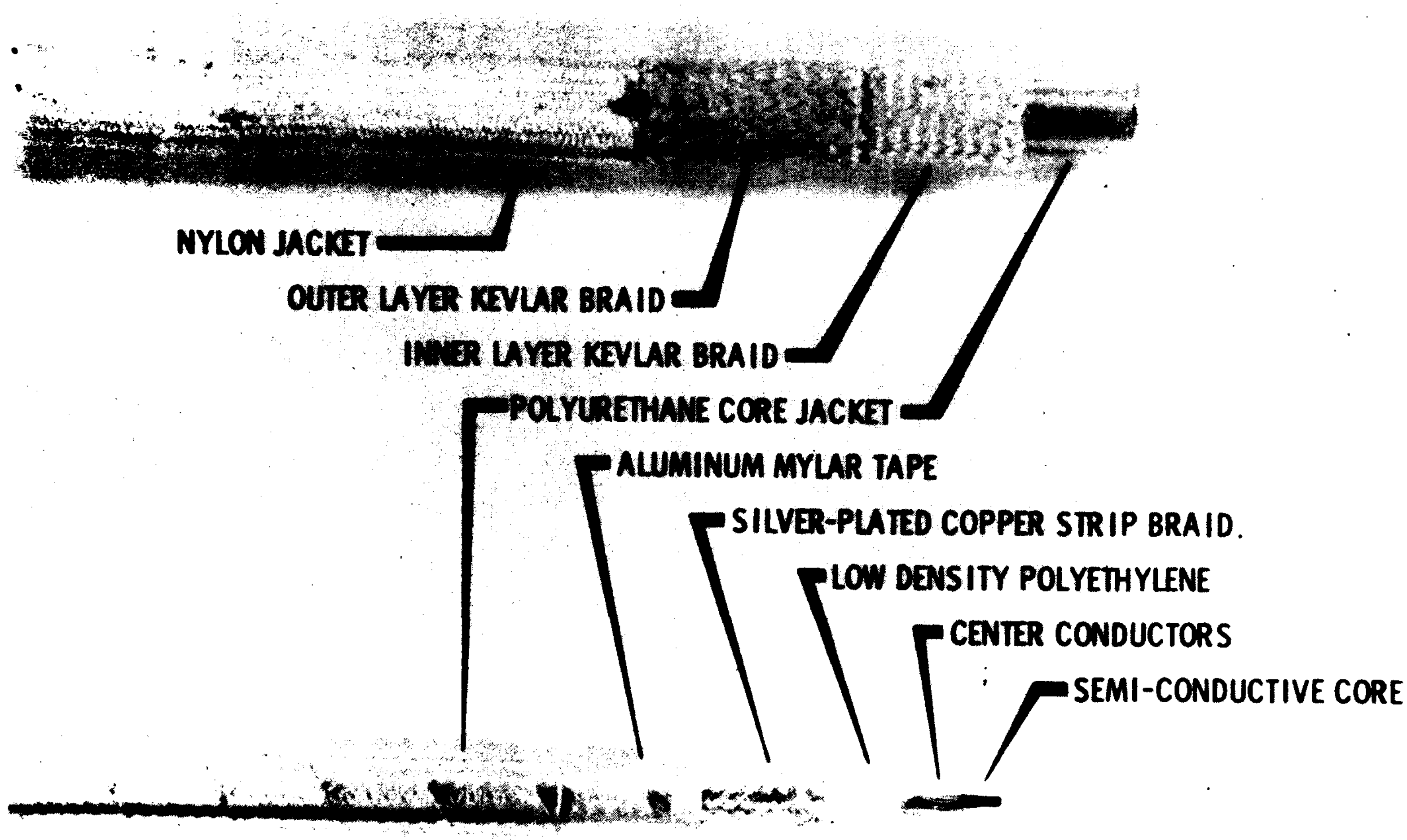

Figure 49. Kevlar Braided Coaxial Pilot Cable

A fourth difficulty developed in the spring of 1976 when two sources reported significant strength reductions in Kevlar cables when exposed to sea water during actual usage. This theory has now been dispelled.

Finally, a continuing and plaguing problem is sample cable fabrication and delivery from a qualified cable manufacturer at a reasonable and predictable time.

1. Pilot Cables

The purpose of the pilot cables (Figure 49) was to expose design problems and ascertain the feasibility of developing the Kevlar coaxial cable for the desired strenuous usage. The cables were designed from past experience and represented the state-of-the-art.

a. Center Conductor

To accommodate up to one percent elastic elongation, the center conductor would require a generous helix around an elastic filler core which provides constructional stretch. The prescribed helix was 36° around a 0.191 cm filler core. In addition, some of the copper was moved from the center conductor to the return, which kept the loop resistance constant. This procedure minimized the size of the wires around the core.

Two pilot cables each 610 meters long were procured. Both were of the same design, except that one length used soft, annealed copper, while the other used a cadmium, chromium, copper alloy (PD135) which possessed better fatigue characteristics. However, subsequent conductor testing in the NAVFAC-sponsored Conductor Development Program revealed no significant mechanical performance advantages with this alloy. In addition, the material was more expensive, hard to obtain, and much more difficult to form in cabling. Because of this and the good performance of soft copper, the material has now been dropped from the program.

b. Return Conductor

The precedential design for the return conductor in Kevlar-reinforced coax had spiral round wires around the dielectric core to provide constructional stretch. Attempts to use braided round wire returns by others failed due to notching at the cross overs. Therefore, based on the amount of copper required and the overall cable diameter constraints, 120 each, 9 mil wires were used for the return. This presented a difficult manufacturing problem, particularly in long continuing lengths.

c. Kevlar Braid

Two passes of Phillystran braid were used to develop the maximum strength within the fixed cable diameter of 1.78 cm. Phillystran, a resin impregnated strand, was chosen for the abrasion resistance and non-twisted flat geometry which minimizes pressure at the braid crossings. These braids were laid over a polyurethane jacketed electrical core. This jacket was expected to provide good bedding for the braid and allow easy connector sealing utilizing urethane molding techniques at the lower end of the cable.

Finally, a thin, tough nylon braid was used as the outer jacket of the cable. This jacket, bonded by urethane to the Kevlar braid, provides mechanical and ultraviolet protection and will not slip or buckle in multiple cable winching operations.

The NAVFAC braid investigations proved, as expected, a strong dependence of cable bending fatigue life with braid angle. The investigations also revealed, along with supporting evidence from DuPont, that significant bending life can be achieved through the proper selection of braid angle, sheave size, lubricants, impregnation, etc.

With this evidence and the recognition that an optimum fit would be required in choosing the braid design, i.e., maximum strength at minimum bending diameter and stretch, the pilot cables were ordered with three different braid angles; 14.6°, 21.8°, and 29.9°. These samples were to be rigorously tested in tension/tension cyclic bending and long-term static tension fatigue.

The overriding problem in this program has been to obtain responsive delivery of cable samples from a qualified manufacturer. In general, cable manufacturers find the cable development effort unprofitable, particularly as in this program, where significant problems may be encountered. Major production equipment must be scheduled and made available. Therefore, sizable delays should not be surprising in view of four to six month delivery schedules for standard production cables. Each iteration on a prototype cable is rescheduled through production equipment with a low priority.

2. Pre Pilot Cable

The first pilot cable was run during the FYTQ. The Navy project engineer witnessed the application of the return conductors on the core at the cable factory. Considerable difficulty was experienced in maintaining good geometry without crossovers or gaps between the many wires. Obviously, special

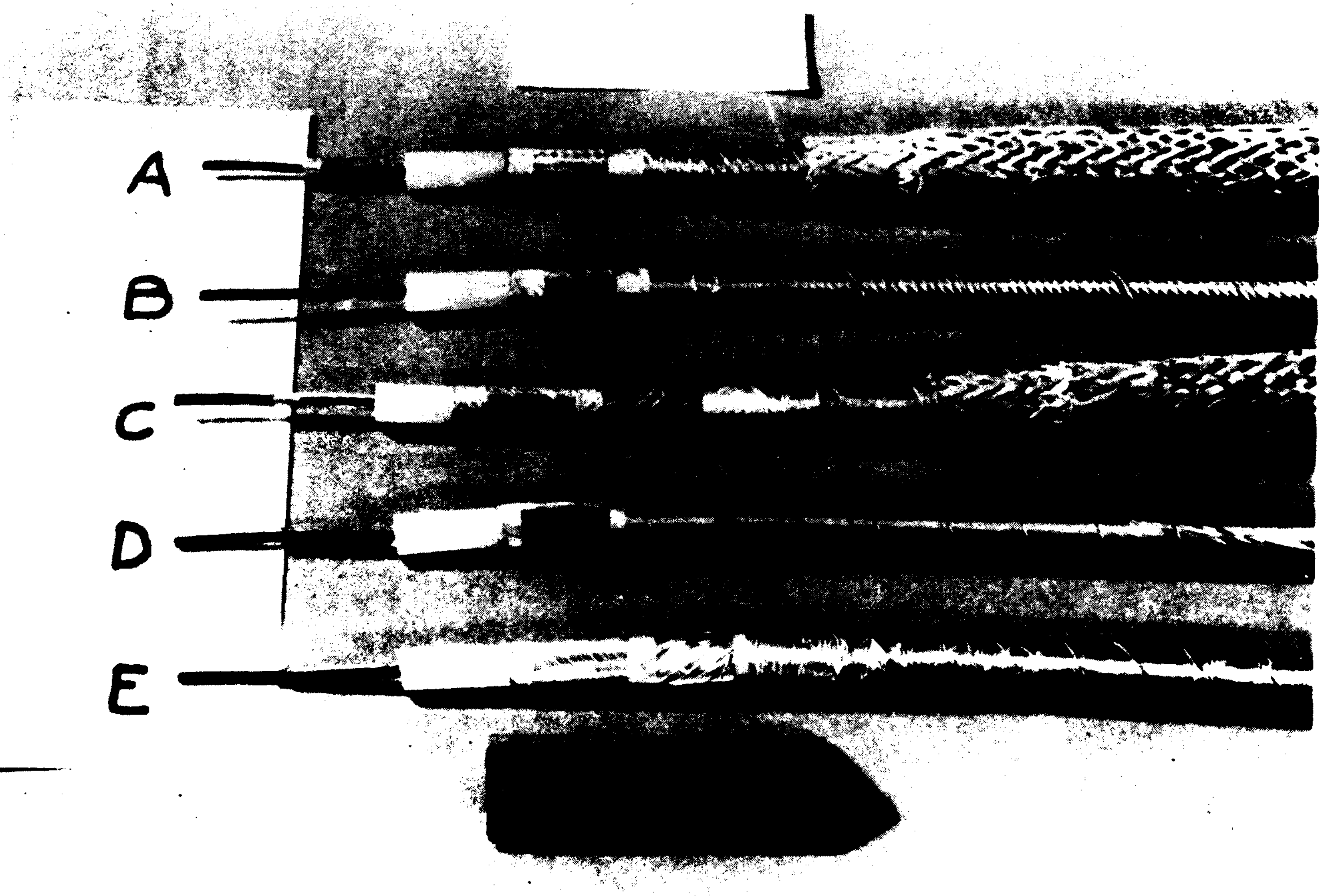

Figure 50. Five Candidate Coaxial Cables

equipment would be required for a continuous long length of cable. This expense, plus the risk of further failure, would clearly make the cable exceedingly expensive. Also, the center conductor did not meet specifications; the lay angle was 18° instead of the designed 36°.

Since approximately 610 meters of insulated center conductor were to be scrapped, a decision was made to utilize this core to experiment with different techniques of applying the return conductor to the core, and to observe the criticality of the helix on the center conductor by subsequent tension/cyclic tension testing.

Five unique candidate return samples were fabricated (Figure 50). The principal sample was based on the success of using flat Kevlar strands vs. round strands in braids, and used a flat ribbon copper braid for the return as shown in Sample A, Figure 50. This approach was to reduce notching at the crossovers by reducing the crimp angle and spreading out the pressure. This sample would also be easier to manufacture, particularly in long lengths. Specifically, the ribbons can be easily replenished on the bobbins of the braider as they individually run out. This is the same approach used in the Kevlar braiding process. Finally, using this design, the principal machinery required to fabricate the entire cable is the lower cost braiders, which also allows for more flexibility in design changes and fabrication sources. The major question to be answered was: would the braid survive bending under load?

The second sample, model "B", simply wrapped the core with one pass of ribbon. This approach was to reduce the number of small wires, but still possessed the same types of problems encountered in a single pass of round wire.

Model "C" used two passes ribbon laid in opposite directions. This would place more copper and avoid the over-and-under crimp of the braid if that had proven a problem.

Model "D" was the original design in which 120 small wires were helixed around the core and had previously described problems. Model "E" is the same, but uses two passes in opposite directions.

These cores were taped with an aluminum-faced mylar tape and jacketed with the specified polyurethane jacket. Thirty meters of the two most promising candidates (A and B) were then overbraided with surplus Phillystran, which allowed mechanical testing to prove out the core. A 22° braid angle was used with enough fiber to produce a 6350.4 kilogram breaking strength.

a. Testing

Stress/strain, cyclic tension and bending tests were conducted on the prepilot cables. Cable "A" was tension-loaded from 0-12.5 kilonewtons (20 percent of break strength for 1105 cycles. The characteristic impedance of 45 ohms was unchanged by the testing. Time Domain Reflectometer measurements also revealed no variation. The cable was then cycled an additional 10,882 cycles at 0-18.7 kilonewtons, which produced a one percent elastic stretch without apparent degradation. However, upon subsequent dissection of the core, the predicted buckling of the center conductor was observed. This securely validated the requirement for built-in constructional stretch, along with the necessity of rejecting the original pilot cable due to the low helix angle of 18°. Fortunately, the braided return survived this phase of testing without damage.

The prepilot cable "A" was then subjected to more critical testing for the braided return of cyclic bending under load. The cable was tensioned to 12.5 kilonewtons (20 percent of break strength, approximately 0.5 percent elongation) and bent over a 20:1 sheave to cable diameter ratio for 4000 cycles; at this time, the Kevlar braid failed. This, in turn, parted the electrical core. Measurements during cycling showed negligible change (less than five percent) in the characteristic impedance and capacitance. Again, dissection of the cable showed no damage to the braided conductor return.

The prepilot phase of the program was extremely productive and validated the necessity for careful center conductor design. This phase proved that a copper ribbon braid could be used which would render the cable much easier to fabricate. Thus, a cheaper and more versatile core for other coax sizes and applications is produced. Also, the emphasis of the development returned to the bending fatigue problems of the Kevlar braid: failure at 4000 cycles of bending due to abrasion.

A second effort in the prepilot phase was initiated to improve abrasion resistance of Kevlar braid. A new variety of Phillystran was developed which utilized a superior resin system and a silicone surface lubricant. This coating was applied to a residual electrical core using a 25° and 30° braid angle on two different lengths. A thin nylon jacket which was securely bonded to the Phillystran braid was also applied. This produced effective cable with a 0.675 O.D., a 100 kilonewton BS, an in-air weight of 100.9 kilogram/30.48 meters, and an in-water weight of 21.7 kilograms/30.48 meters.

b. Prepilot Phillystran Testing

Table 14 summarizes the information obtained from the second series of bend tests on the prepilot cable. As shown, some scatter is in the data; however, it is possible that the low values are traceable to poor terminating techniques. Additionally, since cables tested on the right side of the machine consistently abraded and failed much earlier than those tested on the left side, it appears that there are either sheave alignment problems or an unbalanced tensioning device.

Concerning the cable, the following general observations were made after failure:

- The nylon cover was worn on the underside where it was in contact with the sheave; but was not worn through.

Table 14. Cyclic Bend Over Sheave Cable Tests

Sample Number	Number of Cycles to Failure	Tension (N) (% of B. S.)	Braid Lubrication
1.	1640	12450 (20)	Dry
2.	4168	12450 (20)	Grease
3.	1270	12450 (20)	Grease
4.	1000	12450 (20)	Grease
5.	186	18682 (30)	Grease
6.	132	18682 (30)	Grease
7.	524	18682 (30)	Molylube
8.	756	18682 (30)	Molylube
9.	3076	18682 (30)	DuPont Wax
10.	2048	18682 (30)	DuPont Wax

- Also the outer surface of the outer Kevlar braid was slightly worn where it was against the sheave, but was in excellent condition elsewhere. The adhesive bonding the Kevlar to the nylon was not visible in the area of the breaks.
- Wear between the outer surface of the inner braid and the inner surface of the outer braid was indicated. Apparently, the two layers move in relation to each other. None of the adhesives had penetrated through to this area.
- The inside surface of the inner braid was clean and smooth, and showed no signs of rubbing between the braid and the electrical core.

Although the condition of the electrical cores were not important to this series of tests, they were examined and provided the expected results. The polyurethane jacket and the polyethylene dielectric were both in good shape. Except for being firmly pressed against the outer conductor, the metalized foil had no rips or holes. The inner conductor survived with no kinks or buckled sections. Finally, the outer round wire conductors failed as in previous tests.

In conclusion, the only apparent damage to the cable appears to have been caused by the two layers of Kevlar rubbing against each other.

3. Future Efforts

Production of a pilot cable, based on the modified design using ribbon braid of soft copper, will begin as soon as data regarding the ideal braid angle are available (Figure 51). The present plans are to include a layer of mylar tape between the Kevlar braid layers to eliminate abrasion. Sample lengths of this

NAVSEA KEVLAR COAXIAL CABLE

CABLE CHARACTERISTICS

Imped: 500 kHz to 1 mHz = 40 ± 8 Ω
Cap: 39 ± 7 pf/ft.
Atten: Max at 500 kHz = 1.5db/1000 ft.
Cent. Cond = 1.67 Ω/1000 ft.
Out. Cond = 1.31 Ω/1000 ft.
BREAK STRENGTh = 20,000 lbs.

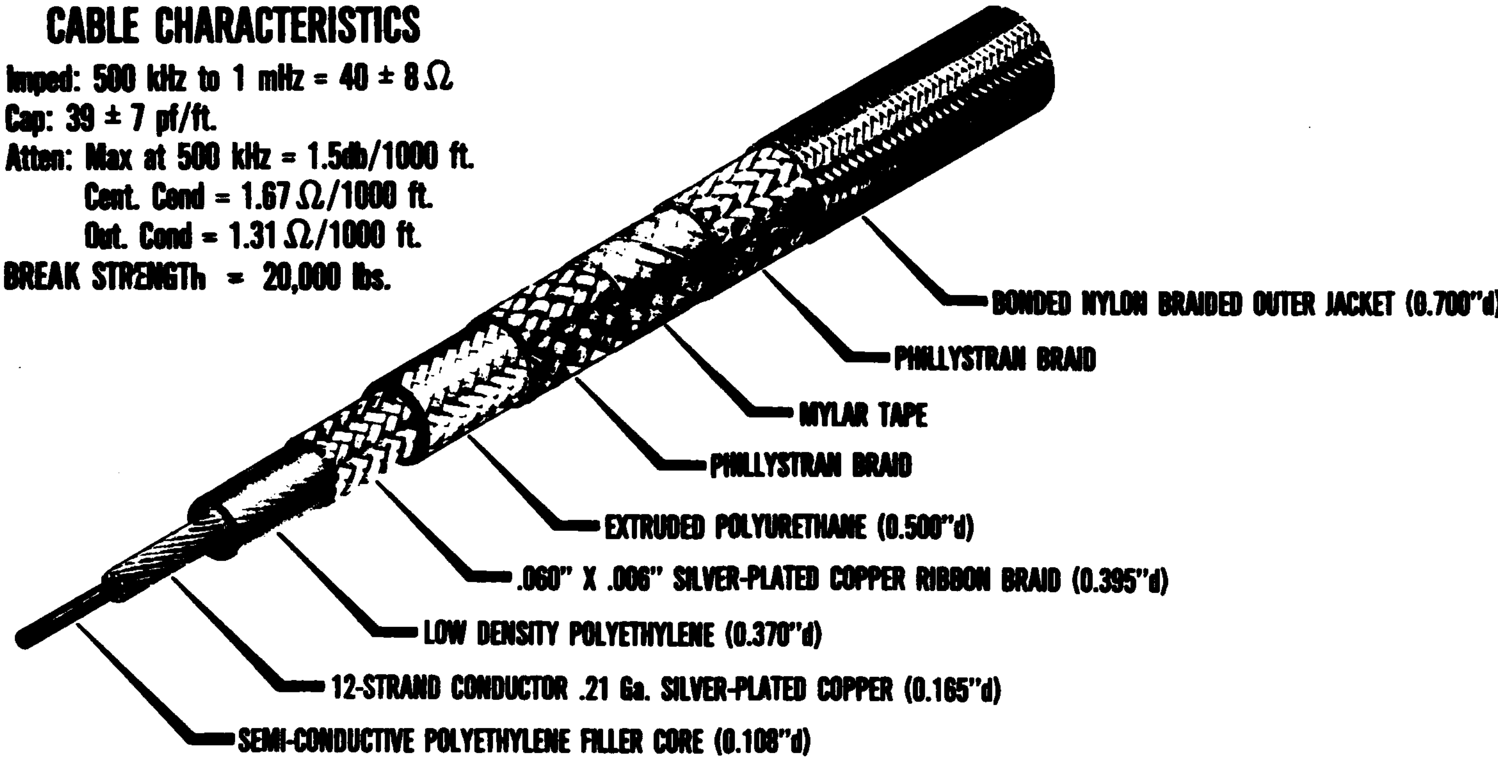

Figure 51. Final Design of Coaxial Cable

cable will be tested at Philadelphia Resins Corporation, as per contract agreement, and at NRL. Additionally, when the actual design is established, a new math model will be generated. The results of this model, and of the mechanical tests performed on the pilot cables, will be monitored carefully to ensure an optimum cable design.

XII. SUMMARY

This report covers the FY76 and FY77 progress that has been made in assessing and using Kevlar fiber as tension members in both ropes and cables. The unique performance of this material required prior studies of both its mechanical and physical properties, leading to these efforts of optimum construction techniques in order to capitalize on those properties.

Studies of both the braid constructions and electrical conductor configuration were most essential to the entire program. Investigations such as the long term tension fatigue, wet tension fatigue and cycling fatigue tests have provided an ability to predict long term performance; and finally, the materials usage at sea has added a measure of confidence in these predictions.

The work described in this report has not only increased the Navy's knowledge in the use of ropes and cables, but also the capability of industry to supply these items.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report covers the work conducted under the NAVFAC sponsored Kevlar Cable Development Program, and, in addition, describes several related projects. The principal focus of this program was to develop Kevlar as a strength member in general cable and rope applications, including other aspects such as terminations, electrical conductors and user experience.